COHERENT Thz SOURCES: PRESENT STATUS AND THE POTENTIAL OF NEW APPROACHES

Final Technical Report

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The main aim of this report is to give a state of the art view of the different approaches toward the realisation of THz sources. The report concentrates on semiconductor based sources which can be integrated in MMICs.

At the lower end of the spectrum in the 100 to 700 GHz range several commercially available semiconductor sources operate at room temperature. Field effect transistors and oscillators such as IMPATT diodes or Gunn oscillators have reached frequencies between 100 and 200 GHz with power levels well above the 100 mW range.

Due to the advances in semiconductor growth techniques new concepts for the realisation of THz sources can be persued. The most interseting concept is the Voltage driven Bloch oscillator, which would lead to a coherent and widely tuneable source.

A second concept is the intersubband laser already demonstrated for infrared frequencies.

A quite promosing approach is the current induced generation of collective excitations- plasma waves-to generate tuneable radiation in the THz region. This concept combines classical methodes of carrier bunching with confinement concepts and the shaping of bandstructures .

Finally THz radiation generated by short pulses offers also a new source with a wide frequency range for coherent spectroscopy.

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SUMMARY

The region of THz frequencies extends from 100 GHz to 10 THz which is in the intermediate region between far infrared radiation and microwaves. Although this part of the electromagnetic spectrum has not been much used up to now there is an increasing interest in developing devices to open this frequency region for technical applications. The main demands for THz devices are in radar ranging systems and in high frequency characterisation of materials and microelectronic devices. Current research activities on applications in communication technologies, robot navigation, conservation technologies and tomography are stimulated by their enormous economical potential.

The main aim of this report is to give state a of the art view of the different approaches toward the realisation of THz sources. The report concentrates semiconductor based sources which can be integrated in MMIcs.

At the lower end of the frequency spectrum in the 100 to 700 GHz range several commercially available semiconductor sources operate at room temperature.

Field effect transistors and " classical" oscillators such as IMPATT diodes or Gunn oscillators have reached frequencies between 100 and 200 GHz with power levels well above the 100 mW range..

At present the frequency range above 300 GHz can only be reached by the technique of upconversion with highly non-linear elements and an additional filtering to select specific harmonics. However the upconversion is accompanied with a power loss of 3 orders of magnitude for the gain of one order in frequency. For the generation of semiconductor oscillators in the 500 to 700 GHz range , which operate at room temperature, new concepts will be necessary. None of the present devices have f_{max} - values exceeding 500 GHz.

One of the main challenges for THz source developments is to provide local oscillators with at least 10% tunability and power levels in the order of 1 mW to allow applications in continuos spectroscopy and remote sensing.

In the higher frequency region from 700 GHz to 10 THz no semiconductor based source meets the requirements necessary for practical applications.

A source which basically meets some of the requirements is the p-Ge laser. In the cyclotron mode tuning is possible between 0.8 and 2.7 THz with one single crystal. With two crystals the whole range from 0.8 to 5 THz can be covered. Emission powers in the 100 mW range are achieved. The main drawbacks are the necessary cryogenic operation temperature and the magnetic field. Further work is necessary to increase the operating temperature to liquid Nitrogen and the pulse length to ms.

Due to the tremendous advances in semiconductor growth techniques new advanced concepts for the realisation of THz sources can be persued. The most interesting concept is the realisation of a Voltage driven Bloch oscillator , which would lead to a coherent and widely tuneable source. However this concept is most difficult , since it requires extremely homogenous superlattices which have not been realised yet.

A second concept is the inter- subband laser already demonstrated for infrared frequencies. There is a quite large chance for the realisation of this concept, which will however lack a significant tuning range.

A quite promising approach is also the current induced generation of collective excitations -as plasma waves - to generate coherent and tuneable radiation. This approach combines classical concepts of carrier bunching with confinement concepts and the shaping of bandstructures through bandstructure engineering. The plasma wave generation can provide a significant tuning range at power levels in the mW range.

Finally THz radiation generated by short pulses offers a coherent source with a wide frequency range. It allows already at present coherent spectroscopy in industry and medicine in areas where costs are a secondary issue. The drawback of this source is that it is quite costly and bulky.

A : Present status of available solid state sources in the 100 to 700 GHz-range

Introduction

The spectral region between 100 GHz and 1THz has long been lacking compact solid state sources. Electronic oscillators have been making incremental gains for many years and were able to extend their operation to the lower end of the above region. Heterostructure transistors such as high electron mobility transistors (HEMTs) or heterojunction bipolar transistors (HBTs) have shown operation up to 200 GHz. Negative resistance diodes oscillators (tunneldiodes, IMPATT- diodes) are quite effective and cover in principle the whole considered spectral range. Maximum oscillation frequencies f_{max} up to 700 GHz /1/ have been reported for tunnel-diodes and more than 300 GHz for IMPATT- diodes /2/. In these diodes f_{max} is limited due to parasitic positive resistance's in the device and connecting circuits leading to a strong reduction of the negative resistance with increasing frequency /3/. However these limits can be further extended by sophisticated growth- and preparation (contact) techniques which will be able to extend f_{max} into the 1 THz region.

A new and most promising approach is the application of " harmonic-multiplication" techniques based on powerful narrowband pump sources in the 10 to 100 GHz range in combination with highly non-linear elements /4/. This technique has the potential to generate high harmonics with "significant" efficiencies up to THz frequencies. With the availability of strong pump sources with W levels in the 100 GHz-range the whole spectrum from 100 GHz to THz frequencies could be covered with power levels in the mW range.

In the following the state of the art of the presently available source techniques and the potential for near future extensions of the frequency range will be discussed.

A 1.1: IMPATT-DIODES

For radio astronomy and remote sensing of the atmosphere in the 100 to 700 GHz region the use of heterodyne receiver systems based on low noise local oscillators are necessary. This requires all solid state sources which can be monolithically integrated with antennas and receivers to MMICs .

GaAs- and Si- based transit time devices for mm-wave power generation have been developed for frequencies between 100 and 200 GHz with f_{max} values up to 400 GHz. Most recent work on GaAs double-Read diodes for D-band frequencies has demonstrated excellent performance up to 170 GHz /5/. The improvements have been achieved by new design of contacts and tunnelling supporting injection structures. A remarkable RF power of 100mW at 144 GHz with a conversion efficiency of 5% and 20mW at 160 GHz has been demonstrated /6/. It is clear that further optimisation of the double -Read and Tunnet IMPATT diodes will result in sources with mW power levels in the 200 to 300 GHz range.

One of the main drawbacks of IMPATT diodes are their noise figures and small tuning frequency range. A noise figure of 26dB at 170 GHz is a state of the art value. This rather large noise figure is the main drawback for heterodyne receiver applications, while power levels are well in the required range.

To summarise this point it can be stated that IMPATT-diodes will not extend their operation significantly above 300 GHz with power levels in the mW range due to basic limitations in the generation mechanism and the resulting " relatively " high noise figure.

A 1.2: HIGH FREQUENCY TRANSISTORS

Based on the well established technology for low noise pseudomorphic AlGaAs/InGaAs/GaAs Hetero-FETs a new generation of devices is developed for applications to low noise as well as to power amplifiers and oscillators.

The prime issue for the development of the original HEMT devices was the outstanding low noise performance in conjunction with its high cut off frequency. However in the recent time also the power and oscillator aspects of Hetero-FET devices are becoming more and more important, especially for applications in the millimetre wave region(THz region) /7/.

The main application areas of low noise MMICs are satellite receivers and portable telephones in the 10 GHz range /8,9/.

This frequency range has in the meantime generated a large number of chip-systems applications in f.e. the following areas:

satellite- communication
navigation systems for individuals
navigation systems for plains
collision radar for cars.

In the range above 20GHz the combination to multifuntional circuits on a single chip are at present rather rare. There exist a significant number of extremely low noise amplifier MMICs up to frequencies of 100 GHz with figure of merit values which are quite remarkable: at 94 GHz a noise figure of 5.5dB with 14 dB amplification represents state of the art /9/.

Power amplifiers in the 20 GHz range with conversion efficiencies up to 40% have been demonstrated /10/. At 35 GHz a value of 1W d.c. power has been realised /11/. Several functions as mixers, phaseshifters and switches have been demonstrated in MMIC-technology.

Only recently these schemes have been extended to the upper GHz range the mm-range. Whole complex systems are integrated on a chip. An example is a FM-CW transceiver at 40 GHz on a single chip /12/.

The presently best performances are achieved with InP based HEMT structures , where f_{max} values up to 450 GHz have been reported for 0.1mm gate length /13,14 /.

Examples of presently achieved power and noise levels with pseudomorphic InGaAs Hetero-FETs are: f_{max} of 230 GHz at 0.25 mm gate length with a noise figure of 2.1dB at 94 GHz.

These devices are at present realised as amplifiers for frequencies up to 140 GHz with acceptable gain and power levels /15/. One of the leading groups in this field is the "Center for High Frequency Microelectronics", Univ. of Michigan, reachiing an oscillating frequency of close to 140 GHz in 1994. Through a further reduction of the gate length to 50 nm it will be possible to realise amplifiers and oscillators for frequencies up to 500 GHz within the next decade.

A 1.3: GUNN- DIODES

There has been an increasing demand for low noise high-power oscillators beyond the 100GHz region for applications in high resolution radars , drivers for multipliers in radio astronomy receivers and for spectroscopic studies in the atmosphere. GaAs millimetre- wave Gunn devices have by now reached frequencies in the 100 GHz range with power levels around 100mW. The use of integral heat sinks resulted in significant device performance improvements /16/. Most recently RF power levels of over 130mW at 133.65 GHz , the highest reported to date from any Gunn device, confirm the long predicted capabilities /17, 18/ of InP Gunn devices. The frequency of the device can be tuned between 132 and 151 GHz. This device can compete with Si D-band IMPATT diodes on diamond heat sinks

/19, 20/, which reach frequencies up to 260 GHz. With noise measures below 23 dB around 132 GHz Gunn devices have a much better noise figure than IMPATTs /21/ and are therefore more widely used now as drivers for multipliers /22/.

Gunn oscillators with power levels well above 100mW at 100 GHz are commercially available and used in many scientific measurement systems.

A 1.4: RESONANT TUNNELING DEVICES

In the early 1970s researchers from IBM realised resonant tunneling in double-barrier diodes /23/ , which displayed novel transport phenomena /24/. A large number of publications on resonant tunneling in semiconductor heterostructuers can be found in the literature, most recent state of the art reviews have been published by Brown et al. /25/ and Lui and Sollner /26/.

For high frequency applications Resonant Tunneling Diodes (RTDs) have proven their usefulness through the quite significant negative differential resistance and high f_{max}. Applications as oscillators and switches have been realised reaching to very high frequencies. Oscillators made from the material system GaAs/AlAs have shown operation at room temperature up to frequencies of 420 GHz /1/. In the InAs/AlSb material system Brown et al. /4/ have demonstrated oscillations of a RDT structure up to 712 GHz. These results are analysed to give a f_{max} of 1.24 THz limited by the resonant tunneling and transit times, the highest value reported for any semiconductor two terminal oscillator at room temperature so far. Due to the higher barriers in these structures the current densities could be increased significantly which led to a reduction of the RC time delay.

For the application of resonant tunneling diodes to next generation nanoelctronics a further improvement of device performance will be necessary. However the negative differential resistance is associated with only one dimension . Consequently the injected electron distribution is wide since the two other dimension do not participate in the shaping of the injected distribution. Therefore resonant tunneling devices with well engineered electron injectors have to be developed. Several experimental attempts on tunneling injection through the use of lower dimensional injectors have been reported (see Ref./26/), which have however not been able to improve the basic IV characteristics of the simple traditional structures.

Several challenges must be met before RTDs can be incorporated into circuits of complexity. The most important issue is the uniformity of the diodes. The main advantage of RTDs is that they can easily be integrated in GaAs circuits and that there is no principal limit to reach f_{max} values up to 2 to 3 THz.

A 1.5: THz COMPONENTS : MIXERS AND DETECTORS

All electronic systems for coherent generation and detection of THz radiation rely on the existence of coherent integrated sources for the required frequency range and the high speed detector. The key element to both source and detector at present state technology is the non-linear mixer.

The dominant and most advanced device for mixer applications is the GaAs based Schottky diode. It is among the fastest electronic semiconductor devices available. The reason for this is on the one hand the high electron mobility in GaAs and on the other hand the inherent simplicity of the Schottky junction itself. These two features together with advanced microfabrication techniques enabled the realisation of subfemto-Farad capacitance's. These diodes are therefore widely used through the mm- and submm wavelength range in applications as frequency mixing , frequency multiplication and sideband generation. Heterodyne receivers have demonstrated operation up to 4 THz and routinely used in radio astronomy applications up to 2.5 THz /27/.

Frequency multipliers which typically use the non-linear capacitance of a reverse biased diode have recently demonstrated operation up to 1 THz /28/. Resistive mixer diodes (varactors) can even generate harmonics at much higher frequencies (up to 4 THz) with is however accompanied with a reduction in efficiency /29, 30/. A cascade of two varactor frequency multipliers delivers 250 μW at 800 GHz and 100 μW at 1 THz, using Varactor diodes with extremely high cut-off frequencies /31/. The output intensity can be signifficantly increased by using multiple elements. Liu et al. /32/ have demonstrated a monolithic frequency trippler array with a 5W output power at 99GHz. The aim is eventually to increase the output frequency to above 2 THz. Schottky barrier mixer diodes have been reported with uncorrected noise temperatures well below 10,000K (corrected at about 5000K) at 1 THz /31/.

An unsolved problem is the present superiority of whisker-contacted devices over planar structures: Above about 500 GHz neither the conversion efficiency nor the power - handling capabilities of the planar diodes are competitive with the old fashioned and not reproducible whiskered structures. This is a major obstacle to further circuit integration of these detectors for integrated submm applications.

The development of Superconductor-Isolator-Superconductor (SIS) receivers and mixers has made significant progress in the last years and has pushed operation to around 900 GHz using Nb-AlO$_x$-Nb junctions and up to 1.06 THz with NbN junctions /33/. Excellent noise temperatures have been achieved using open structure and waveguide mixers : a 660-

690 GHz receiver system for astronomy applications has given a noise temperature of little over 200K over the whole band. However a catastrophic increase in system noise for superconducting structures above the transition temperature is observed. As an example at around 900 GHz Al structures yield noise temperatures of 2000K and Nb structures of 800K at 800 GHz and 2000K at 1 THz..

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A 2.1 : p-Ge FAR INFRARED LASERS

Introduction

In this part the present status of solid state p-Ge far infrared laser is reviewed. The operating principle of these lasers based on bulk semiconductors is to induce population inversion of hot carriers within the valence band to generate coherent sub-mm and mm radiation. The basic idea is to use the scattering free transit of carriers up to the energy of a strong scattering threshold (optical phonon emission) to provide not only an inverted hot carrier distribution but also a mechanism for a dynamic negative differential resistance.

In high purity semiconductors at low temperatures carriers are strongly scattered when accelerated in external fields up to the optical phonon energy $\hbar\omega_{op}$. They gain the energy practically collisionless from the field. If we consider a p-type semiconductor with a light and heavy hole mass m^l and m^h, respectively, the onset of optical phonon scattering for light and heavy holes is at different electric (E) and magnetic (B) fields. The situation is best described in a schematic representation of hole trajectories in the $v_z= 0$ plane in crossed E and B fields. For a given E/B ratio the center of the orbits is the same for both types of carriers. However, the velocity corresponding to onset of optical phonon scattering is quite different: $v^{l,h} = \sqrt{2\hbar\omega_{op}/m^{l,h}}$ since it depends on the effective mass. The situation is best described by a dimensionless parameter $x^{l,h} = v_{op}{}^{l,h}/(E/B)$ which is the ratio between v_{op} and the orbit center velocity E/B. The most efficient pumping process for light hole inversion is when $1 < x^h < 2$ and $x^l > 2$. For these parameters several Landau levels of the light holes lie within the optical phonon energy which leads to an accumulation of light holes in a limited area of velocity space. The heavy holes, however, are streaming: They are accelerated collisionless to the optical phonon energy and scattered back to the origin. As a result of the accumulation the light hole distribution is inverted while the heavy holes are distributed nearly homogeneously up to the phonon energy.

According to a classical calculation for p-Ge by Andronov et al. /1/ with $m^h = 0.35\ m_0$, $m^l = 0.043\ m_0$ and $\hbar\omega_{op} = 37$ meV the optimum condition of the ratio E/B for stimulated emission is $x^h = 1.4$ and $x^l = 2.85$.This predicts a possible emission range between 0.75 THz and 7.5 THz where the frequency for the maximum gain shifts to higher values with increasing B (or E).

A four level pumping scheme illustrates the process quite well. The streaming process is represented by the ground level at $v^h = 0$ and the upper level at $v^h = v_{op}{}^h$. Scattering transfers the heavy holes either directly into the light hole accumulation region or by an emission of one optical phonon to the bottom of the band: After consecutive tunnelling transitions to the light hole band they are accelerated to the accumulation region by the electric field. After the radiative transition light hole - heavy hole the heavy holes are transferred by the electric field back to the streaming process. Detailed calculations of the gain coefficient under the above situation have been performed by Pozela et al. /2/ already before the observation of stimulated emission. The first proposal for a coherent tuneable source came 1958 from Krömer /3/ who suggested a negative mass amplifier (NEMAG). Spontaneous cyclotron emission in a semiconductor was observed for the first time by Gornik /4/ in 1972 and by Otsuka´s group /5/ in InSb. Experimental studies in p-Ge started with the investigation of spontaneous emission /6-9/ in 1981/82 and were followed by the first success in observing stimulated emission by the Russian group around Andronov /10/ and the subsequent observation by Komiyama et al. /11/ and Helm et al. /12/.

Light hole - heavy hole lasers :

The laser crystals are typically several cm long and have a rectangular cross section (0.25 cm^2). Electrical contacts are made by evaporating Indium (with some gold) and alloying at 400° C. All faces of the samples are polished and are parallel within 0.01°. Voltage pulses of up to 1000 V with 1 μs duration have to be applied to the samples with a low impedance high power pulse generator. The typical current through the samples is 200 A, in accordance with the relation $j = 1/2\ pev_{op}^h$, where p is the hole concentration, j is the current density, and $1/2\ v_{op}^h$ is the approximate drift velocity of the heavy holes under "streaming motion" conditions /13/. The pulse repetition rate is around 5 Hz. The experiments are usually performed at 4.2 K with the sample immersed in liquid He at the center of a superconducting solenoid.

The region of lasing extends from somewhat less than B = 1 T for the lowest electric field of E = 1000 V/cm up to 2 T for E = 2000 V/cm. This corresponds to $1.3 < x^h < 1.9$. These results have been achieved by several groups /14, 1, 11, 15-17/. Comparing the magnitude of the signal with the signal obtained from a FIR gas laser and a InSb-Landau source, the emitted power is estimated to reach 500 mW.

The emission spectra consist of 10 - 20 lines with a regular mode spacing of about 42 GHz (1.4 cm^{-1}). Their positions remain fixed with changes in the applied fields. The lasing modes are due to total reflections at the sample surfaces. In the high-gain region some additional lines appear, disturbing the regular structure. The measured line widths are about 12 GHz (0.4 cm^{-1}). By varying the electric and magnetic fields it is possible to obtain lasing between 2.7 THz and 4 THz. There is a general trend towards emission at shorter wavelengths for both higher E- and B-fields /18/. Andronov et al. /17/ and Komiyama et al. /16/ report also lasing between 1.5 THz and 2 THz at lower magnetic fields.

After attaching external mirrors the region of electric and magnetic fields where lasing occurs stays roughly the same. The observed spectra, however, exhibit a dramatic change. A considerably reduced number of lines appears with wider mode spacing and higher amplitude, accompanied by some other less dominant structure. Varying the electric and magnetic fields allows to switch on and off lines on the long or short wavelength side of the spectrum due to a change in the gain spectrum. In this way it is possible to obtain operation of a single line, which was demonstrated for 3.43 THz (114.5 cm^{-1}). In this case two Ge plates act as intracavity interference filter /18/. The polarisation characteristics and the effects of uniaxial stress on the laser oscillations were studied by Komiyama /16/. The gain of the laser is found to be rather small in the range of 5×10^{-3} to 10^{-2} cm^{-1} which explains the necessary high quality factor of the cavity. Most recent results show that the broad band emission can be controlled by an external resonator resulting in an absolute line width of the laser mode of about 20 MHz /19/.

The repetition rate is limited by heating of the laser crystal. At present repetition rates of up to 300 Hz are achieved in 20 mm long samples /20/. Furthermore a slightly increased emission power is observed at elevated temperatures between 10 and 20 K. A optimisation of the cooling (better surface to volume ratio) and a smaller laser crystal volume together with an improved resonator should enable larger repetition rates and possibly also cw operation at temperatures between 10 K and 20 K. The required minimum magnetic fields are between 0.35 and 0.5 T which allows the use of permanent magnets. Thus a further development area should be heat sinking of the laser crystals to a cold finger of a closed cycle 10 K He refrigerator with a room temperature permanent magnet.

Light hole cyclotron resonance lasers:

A concept for a magnetically tuneable laser based on radiative transitions between Landau levels was proposed in the early 1960's by Lax /21/ and Wolff /22/. Lax has suggested a cyclotron maser in InSb pointing out that the nonparabolicity causes unequally spaced Landau levels. Wolff proposed in addition that a sudden decrease in relaxation time above a certain energy level terminates the Landau ladder, effectively eliminating upward transitions by electrons excited into higher levels.

Stimulated cyclotron emission of light holes was discovered during the investigation of spontaneous emission in crossed fields in an extremely pure Ge sample ($p= 1\times10^{13}\ \mathrm{cm}^{-3}$) with the help of a narrowband GaAs detector /23/. A strong emission well above the spontaneous level was observed at certain E and B fields.

The cyclotron resonance (CR) laser based on light hole transitions between Landau levels exhibits a narrowband spectrum which is linearly tunable by the magnetic field /24/.

An important requirement for establishing a negative absorption coefficient from inverted Landau levels (LL) is an unequal energy level spacing. In the valence band of Ge this is automatically the case, since the degeneracy of the Γ_8 band gives rise to the Luttinger (or "quantum") effects /25/. The Landau level spacing in this case is influenced also by the electric field. An inverted carrier distribution in the case of streaming motion in crossed electric and magnetic fields is predicted. In high electric E and magnetic fields B for $E / B > \sqrt{2\hbar\omega_{op} / m^{h}}$, where $\hbar\omega_{op}$ is the optical phonon energy and m^{h} is the effective heavy hole mass, streaming motion can appear where the heavy holes are repeatedly accelerated collisionless to the optical phonon energy and scattered back to the origin. There is a finite probability for heavy holes to scatter into the light hole Landau levels where the carriers are accumulating and having a longer life time for $E / B < \frac{1}{2}\sqrt{2\hbar\omega_{op} / m^{\ell}}$. This is one of the main processes of p-Ge lasers. Streaming motion of heavy holes leads to an increase of the population of light hole LL´s. A population inversion between different LL´s which is necessary for the CR laser is built up due to the depopulation of low lying LL´s by ionized impurity scattering or due to mixing between light and heavy hole states, which leads to a reduction of the lower LL´s lifetime due to streaming motion of the heavy holes /25/.

The lasers with the best performance reported so far were from crystals with two different acceptor concentrations, N_A-N_D = 8x10^{12} cm^{-3} and N_A-N_D =6x10 ^{13} cm^{-3}. The length of the samples parallel to the [1 1 0] crystallographic direction is between 20 mm and 40 mm. The cross section dimensions are 7 mm and 5 mm parallel to the [1 $\bar{1}$ 0] and to the [0 0 1] directions, respectively. This orientation turned out to be important. Two mirrors are mounted at the sample endfaces to form an additional external resonator. The mirrors consist of 50 µm thick Mylar sheets coated by 100 nm Gold; one mirror has a central bore (diameter 1 mm) serving as output coupler. The magnetic field is applied parallel to the [1 1 0] direction and the electric field parallel to the 7 mm wide side of the laser samples.

A limited range of lasing frequencies is found: For doping of 6x10 ^{13} cm^{-3} lasing is observed between 1.2 THz and 1.95 THz. For a doping of 8x10^{12} cm^{-3} a tuning range between 0.9 THz and 1.5 THz is reported. A detailed analysis of the stimulated emission spectra shows that the emission consists of a single line which is linearly tunable by a magnetic field. The line width is about 6 GHz. The reported power levels are in the 5 to 50 mW range /25-27/.

In laser crystals with an impurity concentration of N_A-N_D = 8x10 ^{12}cm^{-3} the tuning range can be expanded by using very homogeneous magnets and an optimized resonator. The stimulated emission of the second range extends up to a magnetic field of 3.7 T. The magnetic field was constant within 0.3 % over a length of 4 cm. Therefore the variation $\Delta B/B$ of the magnetic field throughout the sample was smaller than the relative linewidth of the stimulated emission $\Delta\nu/\nu$= 0.25 cm^{-1}. Thus absorption losses by non-inverted pairs of levels with a resonance energy similar to that of the inverted levels were eliminated /26/.

For both ranges the emission spectra consist of a single line which tunes with magnetic field. No linewidth difference is observed , but the intensity is 2-3 times higher in the high field range. The frequency tunes between 0.84 THz (28 cm^{-1}) and 2.28 THz (76 cm^{-1}). The dependence of the emission frequency on the magnetic field shows a discontinuity between the two ranges at 2.75 T. The corresponding effective cyclotron mass m^{ℓ} (according to the expression for the CR frequency of the light holes $\hbar\omega_c = eB / m^{\ell}$) for the low range at 2.7 T is $m^{\ell} = 0.0472\ m_0$, that of the high range at 2.8 T is $m^{\ell} = 0.0461\ m_0$. It is clear that different pairs of Landau levels are involved in the low field range (B < 2.7 T) and in the high field range (B > 2.8 T) laser transitions /26, 28/.

In samples with a high impurity concentration of N_A-N_D = 6x$10^{13}$$cm^{-3}$ stimulated CR emission was found for magnetic fields between 3 T and 4.5 T. The power of the stimulated

CR emission reached 150 mW. For maximum output power an external resonator consisting of a spherical mirror and a mesh output coupler is used where an output power of 300 mW is found. In general the emission power of lasers with higher impurity concentration is one to two orders of magnitude larger than that of low doped lasers.

There is no linewidth difference to the spectra of the low doped lasers. The position of the line is changed in a range between 1.8 THz (60 cm^{-1}) and 2.7 THz (90 cm^{-1}) by varying the magnetic field. The emission frequency shows the same linear magnetic field dependence as that for the low doped lasers. The tuning curve, however, does not go exactly through the origin if extended to zero magnetic field, this represents a change of the effective cyclotron mass m^l of the light holes between 0.0467 m_0 (3 T) and 0.0469 m_0 (4 T). This increase of the effective mass is due to the non-parabolicity effect /29, 30/.

The maximum repetition rate for 1 µsec long pulses is 10 Hz, for 0.5 µsec pulses 25 Hz, and reaches a maximum repetition rate of 50 Hz for 0.25 µsec pulses. This upper limit for the repetition rate is caused by heating and could be improved by better heat sinking of the laser samples /31/.

The stimulated emission depends on the direction of the electric field and the $[1\bar{1}0]$ direction. Systematic studies of the lasing as a function of the angle φ between the effective electric field (including the Hall field) and the $[1\bar{1}0]$ direction in the (1 1 0) plane have shown that the largest emission range is observed for $\varphi=75°$, where the range extends from 2.4 to 4.4 T /32/. This corresponds to a tuning range from 1.44 THz (48 cm^{-1}) to 2.64 THz (88 cm^{-1}). The emission frequency does not depend on the angle φ.

The total gain for transitions between Landau levels is in the order of 0.1 cm^{-1} /25/, due to the rather small inversion of the light hole population within the Landau levels. The matrix elements for inter-Landau level transitions are known to be quite large. Limiting factors of the lasing mode are on the one hand the impurity limited spontaneous linewidth of cyclotron resonance transitions and on the other hand the nonradiative transition by phonons and an inter-Landau-level Auger-effect /33/. Both limitations are avoided in high purity samples.

Summary:

In summary the p-Ge light hole cyclotron resonance laser has the greatest advantage with its magnetic tunabilitiy. Tuning is possible between 0.8 THz and 2.7 THz with the same laser crystal. The emission power, however, fluctuates quite a lot within this range. In general the power is larger for higher frequencies. Emission powers of up to 300 mW can be achieved in higher doped laser crystals which cover only a limited lasing range between 1.8

THz and 2.7 THz. Since the required magnetic fields are between 1T and 4.5 T only superconducting magnets were useful. The required electric field are higher than for the light - heavy hole laser which makes cooling a more serious problem. A further development is necessary to improve the quality of the resonators so that the cavity size can be reduced. This should improve the cooling efficiency and enable higher repetition rates or cw operation. Most recently Bründemann et al. have reported the observation of intervalence band laser action in Al- doped Ge crystals with volumes as small as 0.03 cm^3/ 34/. This is one order of magnitude smaller than previously reported. A repetition rate of a few hundred Hz with maximum pulse length of 11 ms for Ge-doped crystals was achieved /20/. Such progress in the understanding and performance of p-Ge lasers marks a significant step towards c.w. operation.

However it has been demonstrated by Keilmann /35/ that lasing can be achieved with permanent magnets in fields of 0.8 T for a light to heavy hole laser.. This opens a variety of new application once lasers with closed cycle coolers have been demonstrated. As these lasers have a broad emission range frequency tuning can be achieved with external resonators. There is no real obstacle for the development of c.w. lasers, if the quality of the resonator is improved together the cooling efficiency. In several labs. in Europe and US new materials are persued to lase trough the steaming principle f.e. p-Si and Si/Ge GaAs p-type quantum wells.

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B : Potential of new approaches

B1: Multi quantumwell and superlattice sources

Introduction

Since the formulation of the quantum mechanical properties of semiconductors and the introduction of the semiclassical description of electrons in a periodic potential by Bloch /1/ and Zener /2/, the question, whether it is possible to observe the so called Bloch oscillations in d.c. transport, is still not answered. Early investigations by Kazarinov and Suris /3,4/ were focused on achieving gain and lasing from Bloch oscillations in electrically pumped semiconductor superlattices and quantum wells.

In the following years the discussion evolved on two different, although physically not very different ways. The first one is the concept of the Bloch oscillator which is characterised in quantum mechanics as transitions between Wannier-Stark levels. In the semiclassical description the electron periodically cycles through k-space. This repetitive motion of acceleration and Bragg reflection is called Bloch oscillation. Bloch oscillations are well defined normal modes of the electron in the THz range, if the collision induced broadening of the Wannier-Stark ladders is small compared to the separation of the levels. Another name for this emission process would be photon assisted tunneling. This second characterisation expresses the fact that the radiative transition is indirect in space, that means the initial localisation of the electron is in a different quantum well than the final state. The frequency of the Bloch oscillation is directly proportional to the applied field. However, it is not clear if this tunability still persists in the lasing regime where the high carrier densities lead to a field screening and eventually to a pinning of the internal electric field at the threshold value.

The second concept which meanwhile lead to unipolar laser device is the intersubband emission. This process is spatially direct, that is the electron stays localised in the same quantum well. The disadvantage of this emission scheme is that it is not possibility to tune the frequency of the radiation by the applied field contrary to Bloch oscillations.

A third concept is the use of collective modes to generate coherent radiation. In this case injection schemes which lead to plasma wave instabilities have to be applied

Multi quantum well and superlattice concepts

The first theoretical investigations were done more than twenty years ago. Esaki and Tsu /5/ considered a one-dimensional periodic potential, or superlattice, in monocrystalline semiconductors formed by a periodic variation of alloy composition or of impurity density introduced during epitaxial growth. If the period of a superlattice would be shorter than the electron mean free path, a series of narrow allowed and forbidden bands is expected due to the subdivision of the Brillouin zone into minizones. If the scattering time of electrons meets a threshold condition, the combined effect of the narrow energy band and the narrow wave-vector zone makes it possible for electrons to be excited with moderate electric fields to an energy and momentum beyond an inflection point in the E-k-relation; this results in a negative differential conductance in the direction of the superlattice. This negative differential conductance is crucial to observe Bloch oscillations because the drift velocity reaches the maximum when the separation of the Stark levels becomes greater than the scattering induced broadening of this levels. Bloch oscillations are only observable for DC electric fields well above this maximum in the drift velocity which is equivalent to the condition that the electron executes at least one oscillation within the scattering time.

The next step to a superlattice based emitter came from Kazarinov and Suris /3/. Their work was the first theoretical consideration of amplification of electromagnetic waves in a semiconductor superlattice. In their brief communication they make a rough estimate on the possible gain for the two relevant radiative processes

(1)... diagonal transition (is equivalent to photon assisted tunneling):

the radiative process is a transition from one well to the next one (downstream) where the energy difference is emitted as a photon. This process is tuneable with applied electric field.

(2)... direct transition (subband transition within one well): the radiative process takes place in one well, where the excited state is populated through resonant tunneling from the upstream well. This process is only weakly tuneable with electric field.

In the following article by Kazarinov and Suris /4/ the above brief communication /3 / is extended and formulated more thoroughly. They develop a theory of the electric and high-frequency properties of semiconductors with a superlattice. Due to splitting of the conduction band into minibands it is found that the static current-voltage characteristic has the form of a set of very narrow resonance peaks. The high-frequency conductivity of such a system is also obtained. In the case when a constant current is passing through the system, it is found that amplification of electromagnetic waves can occur in a certain range of frequencies. Moreover, the characteristic amplification frequency depends on the applied static electric field. All these effects are analysed on the basis of a quantum-mechanical description of the motion of an electron in periodic and static electric fields. The transport properties of the system are calculated by means of the density matrix. In an article by Capasso et al. /6/ concerning resonant Tunneling through double barriers, perpendicular quantum transport phenomena in superlattices, and their device applications, the results of Kazarinov and Suris /4/ are reviewed.

Another essential ingredient of getting stimulated emission in a quantum well structure is the confinement of the radiative mode. This problem has to be considered because the conventional dielectric confinement becomes impracticable in the wavelength range above 5 micrometers. Another problem encountered is the thickness of the active zone in comparison to the wavelength, which leads to the consideration of microcavities. This is addressed in the article of Brorson et al. /7/. The authors give explicit results for a dipole placed in the middle of a cavity. The results show, that for a confinement length smaller than the wavelength, the enhancement over the effective mode density in free space varies inversely proportional to the confinement length. Therefore one can get an enhancement by a factor of 15 assuming a wavelength of ~60μm and width of the active zone of approx. 4μm and confinement between two planar mirrors. This enhancement of the effective mode density raises the quantum efficiency by approximately the same factor and is therefore very important.

Babadzhan et al. /8/ and Malov and Zaretsky /9/ make semiclassical calculations for the modulation in the current of ballistic electrons injected into the semiconductor superlattice. The energy of the injected electrons is supposed to be higher than the superlattice potential assumed to be a simple cosine potential in the direction of electron drift. The electrons interact simultaneously with a high-frequency electromagnetic field with polarisation parallel to the direction of electron drift. They find a time and space dependent current modulation of the injected current. For the two limiting cases of energy spread of the injected electrons > photon energy (classical regime) and < photon energy (quantum regime) they give explicit results. In the classical limit the results depend on the relative phase of the electron and the electromagnetic field: absorption or emission processes result depending on the sign of the derivative of the electron distribution function with respect to the k-vector. The authors estimate the laser field necessary to observe the rise in current due to absorption of energy from the laser field to be ~500 V/cm at a superlattice period of ~60 nm for the effective mass of GaAs. They obtain a weak gain of ~1 % for currents in the order of 10^5 A/cm^2.

To enhance the nonradiative electron lifetime Kastalsky and Efros /10/ suggest to apply a magnetic field parallel to the electric field. The authors analyse theoretically the influence of a magnetic field on the electron lifetime in the excited state of a specially designed superstructure allowing electron injection into the excited miniband. In the limit where the bandwidth is smaller than bandgap, they show that the discrete electron energy spectrum arising in the magnetic field dramatically suppresses the acoustic phonon emission rate and gives rise to electron accumulation in excited minibands. The authors claim a suppression of acoustic phonon recombination rate in order of $\sim 10^8$ for a typical structure (a = 30 nm, B = 10 T). One should bear in mind, that all this calculations are performed under simplifying assumptions to get tractable analytical results, especially the momentum conservation is expressed through delta-functions. In real systems of length L there is an uncertainty in momentum conservation in the order of π/L which opens up a much wider phase-space for possible transitions. Therefore this high suppression is somewhat questionable. In a remark they claim that there should be the possibility of radiative recombination across the Landau ladder, but do not take into account the correct selection rules which forbid this process for magnetic field parallel to the electric field except for n-n' = 0, which is exactly the intersubband recombination.

The same suggestion came later once more from Blank and Feng /11/. This work is less precisely and thoroughly than /10/, which cover the same topic with one exception: the authors realised that for magnetic fields not exactly parallel to the growth axis there exist rather strong Landau transitions with $|n-n'|=1$ where n, n' are the Landau indices. This would open up the possibility of magnetic field tuneable emission.

Two new feasibility studies are presented at the same time by Kastalsky et al. /12/ and Hu et al./13/ which apply simple kinetic equations to estimate the relevant lifetimes. Kastalsky et al. /12/ use a second smaller quantum well to reduce the escape rate from the excited level and to enhance removal from the ground state. This concept resonantly extracts electrons from the ground state of the active quantum well and simultaneously reduces the escape rate form the excited energy level. The authors address for the first time the problem of high current densities and suggest a structure of stacked double quantum well diodes mutually isolated by doped layers. Three heterostructure materials are considered: InAs/AlSb, InGaAs/AlAs, and GaAs/AlAs. In all three cases optical gains of 50-90 cm^{-1} were calculated to be present for the photon energy of approx. 0.1 eV. In the second paper Hu et al./13/ suggest the use of a symmetric triple well structure (Borenstain and Katz /14/). Photon confinement should be achieved between highly doped injector and collector semiconductor contacts which serve as photon reflectors. Their later studies showed that plasma losses are the critical parameters in designing an intersubband laser. The estimated lasing threshold current density is in the range of ~ 130 A/cm^2 at 5 THz.

Bloch oscillator concepts

Different new concepts towards the development of a solid state Klystron in the THz-region are discussed by Wirner and Gornik /15/. The first step in this direction was the observation of emission from a density modulated two-dimensional electron gas formed in a GaAs/AlGaAs heterostructure /16/. The Smith-Purcell type emission frequency was tuneable via the electron drift velocity given by the applied electric field. Further concepts persued by this group are the injection of energetically narrow electron distributions in superlattice structures, which could lead to a negative differential resistance.

On the theoretical side Bouchard and Luban /17/ carried out the simulation of the dynamics of an electron in a superlattice by solving the time dependent Schrödinger equation. The initial state is chosen to be a superposition of states belonging to one subband. For an ideal superlattice periodic oscillation of the charge distribution with the Bloch frequency are predicted. By introducing a small perturbation (e.g. randomly distributed small x-variations or a small imperfect layer) the oscillations become damped and are not exactly periodic any more. From this it is concluded, that the main problem in detecting and maintaining Bloch oscillations is a very well defined superlattice structure and not, as believed before the suppression of transitions to higher subbands. Later this results are confirmed by Rotvig et al. /18/ who performed a time-domain analysis of carrier dynamics in a semiconductor superlattice with two minibands. This two band model gives a combination of Bloch oscillation and periodic changes of population of the two minibands for bias values which induce the anticrossing of Stark levels. This is an analogue to Rabi oscillations overlaid with Bloch oscillations at a much higher frequency. In the high field limit the intermediate Bloch oscillations vanish and only the Rabi-like oscillations sustain.

Using the same simple double-well semiconductor heterostructure as above Roskos et al./19/ and Korotkov et al./20/ calculated analytically the major statistical properties of such a system generated by the injected current, including spectral density and amplitude distribution of the continuous-wave quantum Bloch oscillations. The results show that the AC conductance peaks at the frequencies near the Bloch frequency can be either positive or negative. Roughly speaking, the conductance is positive on the left slope of the resonance peak of the DC current (DC I-V curve) while it is negative on the right slope of the peak. For relatively low frequencies this change of sign is clearly understandable as a result of the change in the slope of the DC I-V curve. However, the results are valid for much higher frequencies near the Bloch frequency, where it can be more naturally interpreted as a result of photon absorption or stimulated photon emission respectively.

The results imply that the double-well structure can be used not only for generation of (relatively broad band) spontaneous Bloch oscillations with the characteristic central frequency, but also for amplification of external signals with a frequency close to it. This effect can also be used for excitation of narrow-band autonomous oscillations with frequencies close to the Bloch frequency in high Q resonant cavities with an intrinsic bandwidth less than that of the spontaneous emission. Such oscillators would be very similar in their physical properties to conventional lasers, but would be suitable for the generation of coherent stimulated radiation in the THz frequency range. TASER is the suggested name for this device /21/.

Korotkov et al./20/ studied in addition the statistical characteristics and pointed out similarities and differences between the Bloch oscillations and other well known generators of narrow band radiation. Such a discussion is even more relevant in light of a recent publication /22/ where the statistical nature of the Bloch oscillation process was not taken into account but instead the effect was treated as a direct analogue of Josephson oscillations induced by a DC current. The Josephson oscillations are a sum of completely correlated quantum transitions of Cooper pairs. As a result, the net amplitude of these oscillations is virtually constant even if the phase fluctuations are considerable and the emitted radiation linewidth is relatively broad (delta-function like amplitude distribution). In contrast, the Bloch oscillations are a sum of independent contributions of quantum transitions of uncorrelated electrons. This fact results in the broad probability distribution of their amplitude (Gauss-like amplitude distribution). Such a distribution is typical for spontaneous radiation in other quantum systems and for any wide-band noise passed through a narrow-band filter. Opposite to Josephson oscillations Bloch oscillations represent the limit of completely uncorrelated systems, like the injection through single-barrier tunnel junctions or other two-terminal structures which obey the Tien-Gordon theory. The main result of this theory is that the DC I-V characteristic in the presence of an external AC voltage can always be expressed via its I-V characteristic for vanishing AC field. However, the Tien-Gordon theory is not generally applicable to the studied system, since it reproduces the results only for certain parameter ranges.

Before this work Holthaus /23/ analysed the semiclassical motion of electrons in a single miniband subjected to a strong alternating electric field. Studies of this kind have gained importance due to the emerging free-electron lasers, which allow an experimental probing of the theoretical predictions. For certain values of system parameters a dynamical localisation takes place, which is called band collapse: i.e. the average velocity vanishes /24,25/.

In a second article Korotkov et al. /21/ have carried out a theoretical analysis of the possibility to generate coherent continuous-wave THz radiation using the above discussed double-quantum-well heterostructures. The lasing should take place due to an inverted population of the wells, created by electron flow through the structure under the effect of applied DC voltage. The estimates show that for example a frequency of 3 THz with an extremely narrow linewidth (relative linewidth < 10^{-5}) and a power in the order of 0.1 mW may be generated using structures with area as small as ~100 $(\mu m)^2$, at temperatures up to ~30 K. For the experimental implementation they suggest contacts in the form of heavily doped bars to reduce absorption in the contact layers.

Inarrea et al. /26/ studied the problem of light assisted coherent and sequential tunneling through a double-barrier structure. In the framework of the time-dependent perturbation theory, they have calculated the transmission coefficient and the electronic resonant current. The results presented show very small changes in the resonant tunneling current for AC fields up to several hundreds V/cm which would be difficult to measure in an experiment.

A theoretical study and a critical review on intersubband radiative transitions in multiple quantum-well heterostructures for the generation of IR and FIR radiation was carried out by Smet et al. /27/. The key parameters for electrically pumped unipolar lasers are the spontaneous emission lifetime, oscillator strength, confinement, internal losses, gain coefficient and the required population inversion density., They analysed all above parameters for sustained laser oscillations and compared interwell and intrawell intersubband-transition gain media.

The difficulty in implementing a long wavelength coherent source is attributed to the necessity for an alternative mode confinement scheme, i.e. plasma confinement between highly doped semiconductor layers, to keep the total thickness of epitaxially grown layers within practical bounds. The feasibility of these novel coherent sources critically depends on the non-radiative intersubband transition rates. Numerical simulations of acoustical phonon, polar-optical-phonon, interface roughness, unscreened ionised impurity, and electron-electron scattering were implemented, including their temperature dependence.

The results reveal two extreme wavelength regimes as the most promising for successful demonstrations of an intersubband laser:

a) lasing energies greater than several times the optical phonon energy

b) lasing energies which are a fraction of the LO-phonon energy(Thz).

Smet et al./27/ concentrate on double (triple) well designs, since the superlattice structure suggested by Kazarinov and Suris /4/ leads to the fundamental difficulty of the NDR-driven space charge instabilities (=buildup of high field domains) at the high current densities needed for the emission process.

Two different structures are explored:

a) interwell emission processes (this configuration suggested by Ref. /4/)

b) intrawell emission processes.

The interwell emission processes is the most advantageous since the emission is field tuneable and the system design is less sensitive to process inhomogeneities. There is also a reduced number of nonradiative processes which help rising the quantum efficiency but this quantity is on the other hand compensated by a somewhat reduced oscillator strength. Considering the structure the strongly asymmetric double well structures seem most promising for emission in the high current regime. Another very restricting problem is the mode confinement for radiation wavelengths greater than 5 μm (the interesting range is somewhere from 5 - 600 μm). In this range the usual mode confinement in a dielectric waveguide is not practicable since the layer dimensions have to be on the order of the wavelength. Therefore new confinement schemes have to developed. One suggestion is the confinement due to free carrier plasma screening in heavily doped contact layers (e.g.: /28/, /13/). However, the plasma produces high losses which might be the critical restriction (>450 cm^{-1}). The estimated losses given in /26/ are: facet reflectivityÔs (small): ~38 cm^{-1} for a 300 μm long cavity; phonons (very small): ~3 cm^{-1}; plasma (critical): >450 cm^{-1}; free carrier absorption is also critical due to highly doped thermalisation zones.

For comparison, the realised cascade laser of Faist et al./29/ has typical loss rates for phonons, plasma, and free-carrier absorption of ~9 cm^{-1} because of the considerably higher frequency, facet reflectivityÔs of ~19 cm^{-1} (600 μm long cavity), and optical confinement of ~ 47%.

To estimate the quantum efficiency, the different nonradiative processes are examined separately. For energies above the LO-phonon threshold the lifetime raises with increasing subband separation. In GaAs this values range from .25ps to 1ps. For the InGaAs system this values are higher by a factor of ~2.5 (ratio of effective masses squared). For energies below the LO-phonon threshold the lifetime is about two orders of magnitude higher. In the double well system there is increased lifetime due to Stark-localisation (higher for weaker coupling). The lifetime due to the acoustic phonons is in the order of several hundred ps and may be beyond 1ns for the double well system. Ionised impurities and interface roughness scattering give lifetimes in the same order of magnitude. In the single well system the lifetimes due to electron-electron scattering are in the range of .5ps to 40ps with the higher values for the higher emission energies. Here the double well structure is favourable although the oscillator strength is reduced thereby. For emission energies below the LO-phonon energy, the electron-electron scattering is the dominant nonradiative relaxation process. Generally a magnetic field parallel to the current reduces all scattering rates due to the restricted phase space. Therefore the quantum efficiency below threshold increases, however the additional losses due to the plasma confinement are supposed to outweigh the increase in quantum efficiency. Finally the authors put forward an estimate for a 75 μm laser device and get a threshold current density of

1 - 3 kA/cm^2 and a threshold population inversion of $3x10^{13}$ cm^{-2} under the assumption of 100 stacked and spatially isolated double well systems. This results are far more pessimistic than the estimates of the same group some years before /13/.

The conclusion from /26/ and other studies /16/ is that, electron-electron scattering emerges as the dominating non-radiative relaxation mechanism for the realisation of coherent far-infrared sources. Interwell schemes offer distinctive advantages such as simplicity in design, greater tolerance in design and fabrication errors, weak field tunability of the emission frequency, improved internal quantum-efficiency and all the help from bandstructure engineering to obtain population inversion.

Experimental work on multi quantum well and superlattice sources

Gornik et al. /30/ and Helm et al. /31/ have for the first time observed far-infrared emission due to electronic transitions between subbands in GaAs/AlGaAs superlattices. Population of higher subbands was achieved by applying an electric field in the plane of the layers to achieve a heating of the carrier gas. The radiation was coupled out of the sample by a metallic grating on the surface.

The first article which considers radiative transitions in a superlattice due to ballistic carriers came from Botton and Ron /32/. They investigated the spontaneous emission by electrons traversing ballistically a superlattice in semiconducting heterostructures and found a threshold current density for lasing in the order of 10^4 A/cm^2. The considerations are somewhat crude as they do not take into account an electric field, which has to be applied to get the necessary current. The problem how to get population inversion, i.e. the injection and removal of the electrons is not taken into account.

This problem is addressed by Borenstain and Katz /14/. The authors calculate the nonradiative recombination times for intersubband transitions below the LO-phonon energy under population-inversion conditions in a single quantum well. They state that under these conditions the main nonradiative process is Auger-recombination. Such calculations have been done earlier but without accounting for the degeneracy of the electron gas in the subbands. The use of Fermi-statistics extends the model to systems with low lying subbands which are necessary to supress LO-phonon emission. This situation is a requirement for emission in the FIR-regime. Auger recombination as the major nonradiative process determines thus the threshold current of infrared lasers based on intersubband transitions in quantum-well structures. Nonradiative recombination times in the order of 200-500 ps are derived. The lower values are obtained for larger population inversion, but are less sensitive to intersubband separation and temperature changes due to the degenerate electron gas. Finally they present a rough estimate of the gain in a simple quantum well with an injector and extraction barrier.

In a second article Borenstain and Katz /33/ present calculations for the gain and the threshold current for a quantum well with double barrier energy filters for injection and removal of electrons. The model structure seems promising and could be extended to a multiple quantum well structure. Their theoretical results are very useful but depend strongly on hardly known numbers for the involved time constants (spontaneous emission lifetime, transit time, and scattering time). They find that for the wavelength range 50 - 120μm, the required threshold currents are the lowest and have reasonable values of 10^3 - 10^4 A/cm^2. Finally the authors point out the potential of superlattice based FIR-sources because of their significantly higher quantum efficiency ($\sim 10^{-4}$) as compared to other concepts (e.g. non-linear mixing, p-Ge laser).

In the same year Helm et al. /34/ presented the first observation of infrared light emission from a semiconductor superlattice in a resonant-tunneling experiment. They observed radiation from the three lowest intersubband transitions, proving resonant tunneling to be an effective process of populating high-lying states of the superlattice. The results show that sequential resonant tunneling injection is much more efficient excitation mechanism than Ohmic heating. The conversion efficiency is estimated to be at least one order of magnitude higher in the resonant tunneling configuration. The good agreement between calculated transition energies (at flatband) with measured emission energies is interpreted as indication that the electric field in the wells is effectively screened by carrier accumulation. This could be a consequence of the relatively thick barriers which also are responsible for the observed domain formation in the superlattice. As expected FIR-emission is strongly reduced for subband splittings above the LO-phonon energy indicating strong nonradiative recombination.

Before the experiments of Unterrainer et al. /35/, direct observations of Bloch oscillations were restricted to optical studies (excitations across the gap) of superlattices and double quantum well systems in electric fields. In this case no real transport occurs and the question of field domains (inhomogeneity) is not as important as in DC driven systems. In the optical experiment electron-hole pairs are created that have an energy splitting that is characteristic of a Stark ladder. Of course these states are the quantum mechanical equivalent of Bloch oscillations in k-space, provided that the states are spread over several superlattice periods. The first experimental evidence of this optically induced Bloch oscillations, although in a double quantum well system (instead of a superlattice), was reported by Leo et al. /36/ in a degenerate four-wave-mixing experiment.

A more direct demonstration of driven Bloch oscillations is the measurement of the oscillating dipole moment as performed by Roskos et al. /19/. The authors use a time-resolved coherent technique for the detection of the submillimeter-wave radiation resulting from the spatially oscillating charge. They can trace up to fourteen oscillations at 1.5 THz before phase relaxation destroys the coherence of the oscillating wave packet. The electrons are excited across the gap through a short (~160 fs) laser pulse. The emitted radiation is detected by an optically gated dipole antenna.

About a year later the same type of experiment was carried out with a superlattice sample (35 periods) by Waschke et al. /37/. The emission could be tuned over a rather wide range from 0.5 to 2 THz by the applied electric field. To determine the origin of the THz emission, the data from the time resolved measurements are compared to photocurrent- and differential reflectivity- spectra. This comparison shows, that in the miniband regime the emission depends weakly on the bias, which was ascribed to screening but could be attributed to the non-linear transition regime from flatband to the linear Wannier-Stark regime. In the linear Wannier-Stark regime the authors found exactly the expected bias dependence. In the so called Bloch regime, where the extent of the wavefuntion is over several well no clear dependence on electric field was found.

Recently Dekorsy et al. /38/ reported the observation of coherent electronic wave-packet oscillations in a semiconductor superlattice (35 periods) at room temperature. The Bloch oscillations were excited in a wide-miniband GaAs/AlGaAs superlattice by fsec laser pulses. Several cycles of the coherent electronic motion are observed within the dephasing time of the interband polarisation. The frequency could be tuned by the applied electric field from 4.5 to 8 THz. The observed dependence of the Bloch frequency on the DC bias was within the error range of the expected theoretical values. The somewhat smaller slope in the experimental values could be interpreted as field screening or as argued by Unterrainer et al./35/ as due to domain build-up. As an interesting feature the differential transmission signal shows a linear rise superimposed by the strongly damped THz oscillation. This rise is to the scattered electrons and is responsible for carrier accumulation which disturbs the homogeneous field distribution.

Experiments towards a Bloch oscillator

The first experiment towards evidence of Bloch oscillations in the DC transport regime were reported by Guimaraes et al. /39/. They measured the current-voltage (I-V) characteristic of semiconductor superlattices in the presence of intense THz fields produced by a free-electron laser. The non-linear I-V curves exhibit new structure that can be attributed to photon-mediated sequential tunneling into photon sidebands induced by the electric fields at THz frequencies. These processes are the inverse of the emission processes proposed by

Kazarinov and Suris /3/. The authors expected to see also stimulated emission but give no explanation why they did not see this process. One possibility could be the relatively high temperatures at which the experiments were performed (kT in the order of the separation of the Stark levels). New experiments with better samples did not show this deficiencies but clearly exhibited a tunneling characteristic with two replicas due to the photon sidebands.

Recently Unterrainer et al. /35/ performed similar experiments with the intention to demonstrate the inverse Bloch oscillator. They found appreciable changes in the I-V characteristics of a semiconductor superlattice if the Bloch frequency is resonant with the external THz field and its harmonics. The observed peaks at resonance bias grow with increasing laser intensity accompanied by a decrease of the current on the low bias side (dynamic localisation). For even higher laser intensities the first peak becomes weaker and an additional peak at about twice the Bloch frequency is observed. At the highest power levels four-photon resonance's could be observed. The increase of current is interpreted in terms of stimulated emission of THz photons. The gain is estimated to in the order of 10^{-5}. As mentioned by Dekorsy et al. /38/ this experiment also exhibits a somewhat smaller slope of the Bloch frequency as a function of DC bias, which is attributed to formation of high field domain across a part of the superlattice structure.

A new technique for the measurement of the intersubband lifetime is the excited state differential absorption spectroscopy as reported by Faist et al. /40/. Electrons are optically excited from the ground state to the first excited state of a doped quantum well. From measurements of the absorption cross section between excited states, the authors find a lifetime equal to ~0.65 ps for a 8.5 nm GaAs quantum well and ~0.8 ps for a 10 nm InGaAs quantum well. In addition, the experiments unambiguously show that the intersubband absorption line is homogeneously broadened at cryogenic temperatures ($T < 100$ K).

Later the same group /41/ presented also data on lifetime experiments in a modulation-doped structure for states separated from the ground state by less than the optical phonon energy. A lifetime of ~300 ps is found. The determination of the lifetime of the second level in a coupled double quantum well system by differential transmission spectroscopy depends on a number of hardly known experimental variables such as absorbed power, fraction of electrons scattered to this level, width of the probe beam on the sample surface etc.. The observed (or evaluated) lifetime seems too long as compared to more direct measurements.

A direct excite-probe semiconductor lifetime determination in the psec regime was reported by Murdin et al. /42/. The authors used an RF-linac-pumped free-electron laser to determine the relaxation rate associated with intersubband absorption in GaAs/AlGaAs quantum wells having a subband separation smaller than the optical phonon energy. The measurement give quite unambiguously a relaxation lifetime of ~40 ps. The relevant lifetime is quite important for the estimation of threshold currents and gain f.e.. The direct pump and probe measurement thus allows a straight forward interpretation of the data. The problems involved through the interband excitation are not present.

No reliable values for the coherence length of carrier in superlattice structures are available, which is an important physical quantity for the design of a Bloch oscillator and intersubband lasers. Agullo-Rueda et al. /43/ investigated GaAs/AlGaAs superlattices with well (barrier) thickness of 4(2), 3(3.5), 4(3), 4(3.5), 4(4), and 5(3.5) nm. The superlattices were incorporated in the intrinsic-zone of a p-i-n-diode. They used photocurrent spectroscopy with low power excitation and demonstrated that the quantum coherence in GaAs/AlGaAs superlattices increases with decreasing superlattice period D, and that it is maintained for at least ten periods when D = 6 nm. Since the holes are much stronger localised with increasing electric field due to their high effective mass, an the increasing localisation of the electrons is also observed. The overlap between hole- and electron wavefunctions is responsible for the transitions strength. As a consequence they directly deduce the coherence length of the electron wave function from the number of observable Stark ladder transitions. As an additional manifestation of the Stark ladder, the photocurrent showed strong oscillations, periodic with the reciprocal value of the electric field. This gave rise to regions of pronounced negative differential resistance.

Bradshaw and Leavitt /44/ performed differential photoconductance measurements and observed oblique optical transitions between Stark states spanning up to 14 periods in a 3 nm InGaAs - 2 nm InAlAs superlattice. The conduction band wavefunction coherence length is deduced to be 145 nm.

Development of the intersubband laser:

The first demonstration of an intersubband emission based photon assisted tunneling was reported by Faist et al. /45/. The authors report the observation of electroluminescence associated with intersubband transition energies greater than the optical phonon energy and at temperatures as high as 300 K. Optical powers up to a few nanowatts and linear in the drive current have been measured. The Stark shift of the luminescence peak is attributed to the photon-assisted tunneling nature of the transition. The temperature independence of the luminescence in the 10-100 K range and the linearity of the optical power versus drive current are interpreted as evidence of population inversion. The quantum well structure used to observe these findings is much more complex than the original proposal of: Kazarinov and Suris /4/. In a very interesting paper by Kastalsky et al. /12/ a stack of spatially isolated coupled quantum wells are suggested for establishing population inversion instead of a simple superlattice. This design avoids the problems connected with carrier accumulation like detuning from the resonance when the local charge neutrality is not preserved due to the high current densities, and build-up of high field domains. The active zones consisting of three coupled quantum wells are imbedded in highly doped digitally graded regions, which serve as thermalisation layer for electrons coming from the upstream quantum well and also as injector to the next downstream quantum well. The doping assures the charge neutrality within each stage and establishes a constant field. Therefore the voltage drop occurs across the quantum well system for bias above the onset of current. Additional bias changes only the emission frequency via the Stark effect.

The new ideas are the specific injection and removal processes. Injection occurs through a single tunnel barrier . The removal from the second well where the ground state of the optical transition is located is not via resonant tunneling as suggested previously but is achieved by a much faster process namely the LO-phonon emission to the ground state of third well which is strongly coupled to the second. Finally the electrons tunnel through the downstream barrier to the thermalisation region of the next active zone. Using this sophisticated structure the Capasso group demonstrated for the first time that population inversion is possible although the excited state lies well above the LO-phonon energy. The emitted radiation was in the mid-infrared regime (~4 μm) . The principle could be helpful for the design of an FIR-laser structure.

Generally this paper and the following of this group demonstrate the importance of band gap engineering to manage the rather complicated task of carrier injection and extraction and the tuning of the involved lifetimes.

Only three month later the same group managed to get stimulated emission based on the above mentioned device. The mode confinement was due to the plasma created by the high doping contact layers. Above threshold the emission linewidth is reduced from 750 cm^{-1} (spontaneous emission in the first device) to 0.3 cm^{-1} (above threshold). Optical powers in of 10 mW in pulsed operation could be achieved. The threshold current density was on the order of 11 kA/cm^2. The name for this new device is quantum cascade laser.

In the following two articles provide reports on improvements of the device structure and a systematic study of operation at different temperatures. Faist et al. /46/ show that the introduction of a setback between the active region and the dopants has a dramatic effect on the spectrum. The emission line changes the line shape from Gaussian to Lorentzian and becomes narrower. Furthermore a blue shift of the emission is observed. The shift in the sample without setback is attributed to the band tail on the low energy side of the two-dimensional density of states which is absent in the samples with setback. In the same way the line narrowing can be understood: the impurities represent long-range fluctuations which lead to large inhomogeneous broadening and change the lineshape to a Gaussian form. The temperature dependence of the performance characteristics is studied in /46/. The threshold current density is assumed to vary exponentially with temperature ~exp(T/T_0). For T_0 a value of ~112 K is found. The threshold current density varies from ~6 kA/cm^2 at 50 K to ~9.3 kA/cm^2 at 125 K. This weak temperature dependence, as compared to interband lasers operating at similar wavelengths, is due to the intersubband nature of the laser transition, due to the physics of optical phonon scattering, and due to the negligible intersubband Auger recombination rates. The reported peak optical power vary from 32 mW at 10 K to 18 mW at 80K for a 1.2 mm cavity length. The derived slope efficiency is 52 mW/A at 80 K which corresponds to an estimated differential quantum efficiency of ~0.034 per facet per stage for a 14x720 μm^2 sample.

Another intersubband laser device is presented by Faist et al. /47/. They report the realisation of a intersubband laser based on a vertical transition. This type of transition is not bias tuneable any more. However, as the foregoing indirect transition laser devices show, the electron density in the upper level is locked at the threshold level and therefore the emission is not tuneable above threshold. In this new design the confinement of the electrons in the excited level is achieved through the proper design of the digital grading region (Bragg confinement). In the same way the lower level is energetically situated in a region of high transmission to enhance carrier extraction. A threshold current density of ~3 kA/cm^2 and a measured slope efficiency of 300 mW/A could be achieved.

The last development is this field is a quantum cascade laser in the 8 to 14 μm regime reported by Sirtori et al. /48/. The structure, as before, contains a 25-stage coupled-quantum-well active region. The waveguide design is optimised to enhance optical confinement and reduce losses associated with the interface plasmon mode, by taking advantage of the dispersion of the refractive index of the contact layer near the plasma frequency. The peak optical power is 30 mW and the threshold current density ~2.8 kA/cm^2. Operation up to a temperature of 130 K is reported. The slope efficiency at 100 K is ~0.1W/A, corresponding to a differential quantum efficiency of 5.4 % per stage. This work, combined with previous results on shorter wavelength quantum cascade lasers, demonstrates that the wavelength of these new light sources can be tailored over a wide range by changing the active layers thickness using the same materials.

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B 2: Sources of Electromagnetic Radiation via Plasma Wave Generation

Introduction

If a current flows through a plasma, plasma waves can grow by drawing energy from the current under appropriate circumstances. This phenomenon is called the current driven plasma instability (CDPI), and is well known in gaseous plasmas /1/. It can be viewed to be the result of plasma wave generation due to net downwards single particle transitions, arising from the population inversion in particle distribution (in momentum space) produced by an imposed excitation (f.e. electric field). Population inversion can also be achieved by other means (e.g. optical pumping, various forms of carrier injection, etc.), and would also lead to generation of plasma instabilities. Certain types of such instabilities have already been used to generate and amplify electromagnetic waves in gaseous plasmas /2/.

Past attempts in theory and experiment, to investigate analogous instabilities in solid state plasmas /3,4/, were not succesful mainly due to very high scattering rates by impurities, defects, etc., in the systems studied. Modern semiconductor nanotechnology offers considerable flexibility in the material engineering which can overcome these difficulties. Lower dimensional systems with modulation doping can have significantly reduced electron-impurity scattering rates, so that very weakly dissipative plasmas can be achieved at low temperatures (which suppress electron-phonon scattering). Bakshi and Kempa have systematicaaly investigated the feasibility of CDPI in a variety of lower dimensional solid state systems: type II superlattices /5/, type I superlattices /6,7/, ballistic systems /8/, counter-streaming arrangements /9/, quantum wires /10/, heterostructures /11/. They predict in a number of these systems the ocurence of instabilities. However they require the best existing samples very close to the present technological limits /9/. The main reason for this is that extremely high drift velocities in the order of the Fermi velocity are required to generate CDPI in those systems, and the requisite high driving fields "heat-up" the carrier distribution, effectively eliminating the instability.

In a different attempt Bakshi and Kempa examined periodically modulated lower dimensional systems such as quantum wires with a superposed periodic potential modulation along the length of the wire /12/. This leads to mini-band formation in the electron energy spectrum. Under the influence of the applied field only the partially occupied topmost miniband can support dc current flow, through the corresponding electron distribution shift in the momentum space. This shift creates a population inversion leading to downwards electron transitions, which in turn drive the plasma waves. Since in this arrangement only electrons in the topmost miniband contribute to the inversion, a much lower driving electric field is expected for achieving the onset of the instability. Indeed, they found that plasma instabilities can be generated in such systems at significantly lower driving electric fields /12/, provided also that electron-phonon and electron-impurity scattering rates are sufficiently low. Unlike the unmodulated systems, the instability occurs in the domain of essentially cold electron transport and thus the driving fields do not enhance the dissipative collisions. The initial study based on a modulated one dimensional electron gas (1DEG) using a two-miniband model has now been extended to multi-miniband occupation, employing a selfconsistent treatment of the model system /13,14/. They have also investigated 2DEG with modulation in both directions (lateral surface superlattices, LSSL), and predict also in this system the feasibility of CDPI for certain parameter ranges /13,15/.

All of the systems mentioned above, whether uniform or modulated, are extended in space. An entirely different approach is to consider systems where the boundaries play an important role, e.g. finite length wires /13/. Such systems offer special advantages over the large and open systems. A bounded plasma has several eigenmodes, making it possible to pump the energy from the current to the plasma under a variety of conditions. A bounded system plays the role of a plasma mode resonator. One can also reduce the effects of collisions (impurity and phonon) by reducing the active size of the device below the corresponding mean free path, while the electron-electron interactions which sustain the collective modes are left intact. In addition, plasma oscillations of a bounded plasma couple directly to the electromagnetic radiation and no additional coupling mechanism is necessary. Also in an open plasma the external field is significantly screened, while one can generate strong electric fields in "short" bounded plasmas. Some preliminary results have been obtained for such systems /13,16/.

Conversion of the energy of the growing plasma waves into electromagnetic radiation requires a coupling arrangement, such as a grating. The grating quenches the plasma wave momentum, and electromagnetic radiation arises at the frequency of the plasma wave. For optimal efficiency the grating period must correspond to the plasmon wave number which provides the highest growth rate of the CDPI. The grating-coupling efficiency for unmodulated systems has been determined /17/. For the bounded systems, a separate grating is not required since the reflections from the boundaries serve the same purpose.

The phenomenon of plasma wave generation in non-equilibrium systems (plasma wave instabilities), of which the CDPI is an example, can be used to build amplifiers as well as generators of radiation in the millimeter and submillimeter range. By a proper arrangement of a multi-reflection directional cavity, a laser type coherent generation of the electromagnetic radiation might be possible.

This plasma wave based approach is particularly well suited for the mid-frequency range of 200 GHz to 3THz, the natural frequency domain of plasma oscillations in low doped and high purity semiconductor systems. Operation of typical classical electronic devices (e.g. transistors) is possible, even at high temperatures, due to the collectivity of the macro-charge oscillations. Plasma effects naturally extend this operational principle to the domain of the micro-charge oscillations. There is no "in-principle" restriction to low temperature operation for devices based on plasma (collective) effects, in contrast to the devices based on the single electron transitions. The line broadening observed in the early measurements of plasma resonance's was primarily due to the de-phasing effect. Recent experiments /18-20/ showed that in the lower dimensional solid state plasmas one can not only generate plasmon excitations, but also sustain, at least for a few periods, coherent plasma waves at temperatures as high as 200 K. It is reasonable to conclude, that by providing a mechanism which sustains a population inversion, *plasma instabilities* will be generated in such systems, which can then be employed for device applications.

Uniform Lower Dimensional Solid State Plasmas

The basic formalism which Bakshi and Kempa apply is based on the standard random phase approximation (RPA) for the response, and the Boltzmann equation (which includes the carries-carrier and carrier-phonon, as well as carrier-impurity scattering) for transport /5,6/.

This formalism leads to a dispersion relation for the normal modes of the system $\omega=\omega(\mathbf{q})$, where ω is the (complex) plasma wave frequency and q is the wave number. When $\mathrm{Im}(\omega)>0$ the plasma wave amplitude grows exponentially in time leading to plasma instability. Non-linear damping effects will limit the growth after the amplitude becomes sufficiently large.

The *type-II superlattice* was modelled /5/ as a semi-infinite set of alternating 2D layers of holes and electrons. Under an electric field, applied parallel to the 2D layers, electrons and holes drift in opposite directions, creating an effective distribution with a "two hump" structure, when the driving field is sufficiently large. When the electron drift is of the order of Fermi velocity, the condition necessary for CDPI is achieved. The detailed solutions for GaSb-InAs type-II superlattices show that the type-II superlattice is a possible candidate for generating the current driven plasma instability. However, the currently available samples of the type-II heterostructures have very poor mobilities, and as a result the growth rate of the plasma waves cannot exceed the collisional damping rate. If higher quality samples are fabricated, CDPI might become possible in such systems.

The physical mechanism for CDPI in *type-I superlattices* is carrier population inversion /6/. The applied electric field and the collisions give rise to a two component electron distribution, consisting of the cold component characterised by the lattice temperature and the drifting hot component at the higher carrier temperature. The cold component is the result of collisions of carriers with the lattice phonons and other defects, which tend to slow down the carriers. The hot component is due to carrier-carrier collisions, which do not slow down the carriers but instead cause heating reflected by the broadening of the drifting part of the distribution. The total distribution can therefore, for sufficiently high drifts, develop a "two-hump" structure, i.e. population inversion. This population inversion leads through the standard mechanism of downward transitions to the generation of plasma instability. Detailed solutions for Type-I superlattices have been given earlier /6,7/ for GaAlAs-GaAs systems, with the conclusion that the current driven plasma instabilities may be feasible, especially for the samples with lower densities and smaller inter-layer spacings.

The advantage of the type-II superlattice over the type-I superlattice is in part due to the fact that in the type-II superlattice carriers are naturally drifting in opposite directions increasing the relative drift velocity of carriers, while the disadvantage was the low mobility. One can combine the advantages of opposite drifts with high mobility by arranging a *counter-streaming type-I superlattice*. This can be done by independently connecting individual layers such that electrons in alternate layers move in opposite directions. Such a system (two layers only) has already been fabricated /21/. The system becomes unstable at a lower threshold drift as compared to the conventional type-I superlattice. In this scenario /9/ one can achieve growth rates substantially exceeding the electron-phonon and electron-impurity collision rates (for the best samples available, at ultra-low temperatures), making this a theoretically promising scheme for CDPI.

However, in the above mentioned schemes large drift velocities of the order of Fermi velocity are needed for CDPI requiring fields between 100 and 1000 V/cm. In these strongly non-equilibrium systems, the model assumptions regarding the scattering effects may not hold. For example, since the strong fields drive the carriers to a high drift and also broaden the distribution, the effective collision rates are enhanced, well above their low field values. In order for CDPI to be observed, the calculated growth rates must exceed these enhanced collision rates, and these effective collision rates should be used selfconsistently in the transport calculations.

One of the basic limitations of the above mentioned schemes was the dominance of collisional dissipative mechanisms. A ballistic mode of operation[22] might avoid this effect, and can be expected to promote the feasibility of CDPI. The simplest model of such a system is a pair of adjacent 2DEG layers, where one is stationary, while the other drifts. Detailed solutions for this scheme have been given earlier /8,9/. As expected this scheme produces high growth rates (which are not reduced by scattering) at threshold drifts comparable to the conventional type-I superlattice. The threshold drift in the ballistic case can be further lowered by a counter streaming ballistic arrangement. However, multi-carrier ballistic operation is very difficult to achieve experimentally, and also, it is necessarily limited to very low temperatures.

Bakshi and Kempa also showed the feasibility of CDPI in an array of quantum wires /10/. Each individual wire was taken as an effectively 2D-strip of electron plasma with single subband occupancy. Threshold conditions for CDPI in GaAs quantum wires were obtained, and found to be comparable to the case of 2DEG based susperlattice systems. However, the mobilities of currently available quantum wires are significantly lower than those of 2DEG systems, and therefore CDPI are unlikely to develop in such systems until much better samples are available.

A summary of the growth rates for CDPI in various uniform systems, along with the corresponding dissipative collision rates has been given in Ref. / 9/.

Modulated Lower Dimensional Solid State Plasmas.

Another candidate for the generation of CDPI are periodically modulated lower dimensional systems /12/. Due to periodicity of the density modulation, miniband structure formation occurs in modulated systems. In dimensionally restricted systems (e.g. modulated 1DEG or lateral surface superlattice, LSSL) under certain conditions, the carrier transport caused by an external constant electric field occurs primarily through the movement of electrons in the uppermost, partially filled miniband. For a sufficiently strong electric field this group of electrons can climb up on one branch of the miniband, opening a gap of allowed energy states below the displaced electron distribution. As a result of this population inversion, massive downward single-electron transitions become possible, which generate growing plasma waves.

Basically the same physical mechanism leads to CDPI in unmodulated systems, but instead of displacing the population of a single miniband, which can be achieved with moderate electric fields, the entire population of electrons must be displaced, requiring large electric fields to generate the very large drift velocity. This in turn heats up the carrier distribution and enhances the effective dissipative collision rates leading to the difficulties mentioned in the previous section. For the modulated systems, the electric fields required for the CDPI are small enough to avoid this problem.

These results rely on the assumption that the transport will dominantly occur in the upper most miniband and that the contribution of the lower minibands are small. The displacement of the electron distribution might lead in any case to a negative differential resistance when the carriers climb up to states with lower velocity. This effect may result in an inverted distribution necessary for the appearance of CDPI and amplification of THz radiation.

Most of these problems might be avoided by using a periodically modulated quantum wire system with the additional modulation big enough to open a small gap. Detailed solutions were reported in Ref. /12/ for 1DEG, considering a two-miniband model with a completely filled lower mini-band and partially filled upper mini-band. A sinusoidal potential modulation and T=0 were assumed. The main result was that the onset of this instability occurs for an applied electric field almost a factor of 10 below the threshold for an unmodulated system. The physical mechanism for this instability is the occurrence of the velocity gap in the effective distribution function that opens up due to the shifted distribution in the upper mini-band.

As the lower miniband is completely filled the transport is dominated by the upper band as long as no excitations occur across the small gap. The key to achieve this instability is to partially fill the uppermost miniband in such a way that the applied field will significantly increase the velocity of these particles, creating a velocity gap.

This work has been extended /13,14/ to include multi-minibands for arbitrary periodic potentials. A fully selfconsistent treatment for the ground state potential arising from any given external periodic potential has been developed. The potential modulation along the length of a quantum wire, or wire array can be generated by gating, by periodic etching, or by making quantum wires in narrow "mesa" etched posts. This last scheme allows one to take advantage of the atomic-scale flexibility in the material growth, which can be used to design an arbitrary potential modulation along the post.

Bakshi and Kempa have also applied the above formalism /13,15/ to LSSL which are 2DEG with potential modulations in both lateral dimensions /22/. The miniband structure depends sensitively on the two periods of modulation, and the strengths and shapes of the potential modulations. Achieving CDPI requires unequal periods of modulation and/or potential strengths. The results for a single wire and a comparable LSSL are remarkably similar, showing that under appropriate choice of parameters, the LSSL essentially creates the physics of individual wires. With the high mobilities of currently available 2DEG, the

LSSL can already be expected to have dissipative collision rates well below the achievable growth rates, and can be expected to be good candidates for observation of CDPI.

Confined Solid State Plasmas

The systems discussed above had at least one free dimension, which was the "active" one, along which an external electric field was applied. In these cases growing plasma waves were free to propagate along this direction. In the new scenario a confined solid state systems for generating plasma instabilities is proposed /13/, where the freedom of propagation is restricted by imposing potential boundaries leading to confined plasma waves. Such a scenario has several significant advantages:

1) A bounded plasma has several eigenmodes, making it possible to pump the energy from the current to the plasma under a variety of conditions. A bounded system plays the role of a plasma mode resonator.

2) One can reduce the effects of collisions (impurity and phonon) by reducing the active size of the device below the corresponding mean free path, while the electron-electron interactions which sustain the collective modes are left intact.

3) Plasma oscillations of a confined plasma couple directly to the electromagnetic radiation, and no additional coupling mechanism is necessary to convert the plasma wave energy into electromagnetic radiation.

4) One can generate a strong electric field in "short" confined plasmas. In an open plasma the external field is significantly screened.

5) It may also be possible to achieve the resonant conditions for acoustic phonons in a confined plasma. In this case one might achieve strong reduction of the phonon scattering, or even arrange for a constructive interplay between plasma waves and phonons to strengthen the CDPI.

Preliminary results /13,16/ for confined plasmas, with a periodic potential modulation, and subjected to a constant driving electric field show the characteristic formation of a Stark ladder in the energy gap, and a corresponding strong resonance in the electromagnetic response. The plasma modes of this bounded plasma become unstable in certain ranges of the driving field. Initial results show that the strength of the CDPI is larger with the periodic potential modulation, perhaps indicating that this increases an effective bunching of the "boxed" plasma. A detailed analysis of this effect, including effects of different shapes of the potential modulation, is in progress /16/.

This approach is quite promising . It basically bridges the concept of collective excitations -as plasma waves- to excitations between electric field induced states -as Stark states-. There should be a continuos transition between the two cases. The theoretical analysis predicts quite strong excitations especially in the plasmon domain which is dominant at the low electric fields.

Prospects for Experimental Verification of CDPI.

In the last year the direct observation of plasma oscillations in the time domain has been demonstrated in lower dimensional solid state nonequilibrium systems:

1) Vossebuerger et al. /18/ showed that a transient population inversion of the electron distribution can be achieved in a 2DEG generated by a pulsed laser beam. This effect was strong enough to generate a few oscillations of plasma waves, even up to 200^0K. These oscillations have been observed directly through THz radiation escaping from a grating placed just above the 2DEG. The plasma frequency was in good agreement with the standard equilibrium 2D-plasmon with the grating enforced wave number.

2) Sha et al. /19/ observed coherent sub-picosecond plasma oscillations in a p-i-n diode structure at 80^0K. In this case also the electron-hole plasma was optically generated, and subsequently driven by the strong built-in electric field of diode.

3) Gornik et al. /20/ were able to generate THz radiation due to the Smith-Purcell effect, while Hirakawa et al. /21/ were able to generate plasmon radiation, by passing a dc current along a modulated 1DEG.

Conditions for generation of CDPI were not reached in these experiments. Nevertheless, these observations show that coherent plasma oscillations can be sustained in a variety of lower dimensional solid state systems, even at high temperatures.

Most recently a completely new approach to use plasma waves for the generation of THz radiation was proposed by Dyakonov and Shur /22, 23/. When the electron mean free path for collisions with impurities and phonons is much greater than the mean free path for electron-electron collisions , electrons behave like a fluid and may be described by hydrodynamic equations. Dyakonov and Shur predict that in a Field Effect Transistor these conditions can be met at a certain temperature. They showed similar to Bakshi and Kempa that in a short enough device , an instability should occur at relatively small device currents because of spontaneous plasma wave generation. This might provide a new mechanism for the emission of tuneable THz radiation. A new family of solid state devices is predicted including emitters, mixers and detectors /24/. The main question will be whether the above condition of dominant electron-electron scattering and the necessary boundary conditions can be met. The boundary conditions for the plasma wave generation require a short circuited source and an open circuited drain of the FET channel at the plasma frequency.

Summary

In Summary, amongst the systems investigated so far for achieving CDPI, the modulated lower dimensional systems may be the best. However, one needs a technological advance in order to achieve quantum wires of necessary quality. Perhaps the recently fabricated V-groove quantum wires with their epitaxially defined boundaries will provide mobilities comparable to the high quality 2DEG. Such a development would make CDPI experimentally possible. For LSSL, systems with unequal periods and potentials in the two lateral dimensions need to be fabricated such that the conditions for CDPI are met. The new ideas of using confined plasmas are most promising:

a) one of the possible experimental schemes involves a short vertical "mesa" structure grown layer-by-layer using the molecular beam epitaxy. This scheme can take advantage of the flexibility of growth techniques (MBE, MOCVD) in this direction to "box" the plasma, and it also allows for precise electric field engineering to obtain the best conditions for plasma "bunching".

b) The other scheme is the fluid approach to the generation of plasma instabilities, which would result in sources and non-linear elements for detectors and mixers.

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B 3 : Technical Applications of Terahertz Pulses

Most devices for THz pulse generation and detection are based on electro-optical techniques. Since the pioneering work of Auston et al. /1,2/ and the development of the "Austin--switch" THz signals with pulse duration's of less than 1 ps are accessible. In these semiconductor devices THz pulses are generated by an interplay of carrier generation by femto-second laser pulses and the ultrashort carrier life time in the semiconductor material. Since the frequency of the generated THz signals cannot be externally tuned applications of this technique are restricted.

Semiconductor heterostructures offer another approach. Here, oscillations of charge carriers in quantum wells are related with oscillating dipole moments leading to emission of THz radiation /3,4/. In particular, Bloch oscillators of semiconductor superlattices are promising sources for THz applications. In contrast to most other techniques the emission frequency of these devices can be widely tuned /5,6/. Further progress will be achieved with the development of electrically driven Bloch oscillators. Such devices will work without the laser systems that are up to now necessary for excitation. The greatly reduced dimensions of these Bloch devices will allow their integration on microchips paving the way for a multitude of technical applications.

Other techniques that show potential for THz pulse generation and applications are optical rectification /7/ and Josephson contacts /8/. Only in Josephson junctions the frequency can be tuned similar as in Bloch oscillators by an electrical field. However, their emission intensity is low and future applications of these devices will be limited to the cryogenic temperatures necessary for superconductivity.

Both, optically and electrically driven THz oscillators allow new opportunities in measurement techniques, for example as sources in Fourier or in heterodyne spectrometry. This will open up the THz frequency region which was up to now nearly inaccessible by conventional measurement techniques. Absorption measurements with THz emitters like Austin switches and Bloch oscillators have already shown the advantages of compact measurement systems and high beam intensities compared to techniques with thermal sources /9/. Additionally, the ultrashort pulses enable time-domain spectroscopy at THz frequencies giving the amplitude and phase of the transmitted signals. These THz time-domain characterisations of gases, liquids, and solid state materials allow new insights into the static and the dynamic properties of matter. Investigations on high temperature superconductors have given the real and imaginary parts of the dielectric constants /10,11/.

The Drude-conductivity has been determined by investigations on differently doped semiconductors /12/.

Applications of THz devices in environmental techniques are related to absorption measurement techniques. In frequency tuneable sensors the specific absorption lines of gases in the THz band can be used for fingerprinting air pollutants. Applications for spectroscopy on gaseous systems have been demonstrated on the THz absorption bands of NO /13/. A key technology challenge is the measurement of the hydroxyl radical which is responsible for the ozone decomposition and can be measured only at 2.5 THz or higher frequencies. Programs for the development of critical instrument technologies for environmental measurement techniques are being run by the European Space Agency for example /14/.

Advances in microelectronic development tend towards ultra high speed devices operating at THz bit rates. These are planned for future near field communication systems in particular. However the development of THz-devices requires new device testing techniques at these frequencies. The injection of THz signals in devices under test like high--electron--mobility transistors, resonant tunneling diodes or single electron transistors gives direct insight into their switching dynamics and high frequency behaviour /15/. In a similar way the signal losses and dispersion of chip transmission lines and connects can be deduced /16/. These measurements are currently performed on single frequencies and require frequency tuneable emitters like Bloch oscillators.

One of the main fields for the application of THz emitters and detectors is in radar ranging systems. Despite the strong absorption of THz-radiation in air, the short wavelengths and the small dimensions of emitters and antennas have an enormous potential for near field ranging devices. Such devices can be used for a multitude of purposes in the detection of obstacles by the measurement of distance, motion or acceleration. Applications in automobiles, robots and other mobile systems for orientation and navigation purposes are persued in many laboratories. Additionally, the properties of ultrashort THz pulses open new technical opportunities. One is the time-gated detection of the THz pulses reflected from targets which allows an extremely high discrimination ratio from unwanted signals such as background radiation or spurious reflections. Secondly, the submillimeter resolution accessible with ultra-short pulses permits the use of scale models for determining radar patterns of real-world targets /17/.

Recently, new applications of THz pulses have been demonstrated in imaging techniques /18/: Many compounds can be distinguished by their specific absorption in the THz range. This feature together with the ability to focus the radiation to spot sizes of less than one millimeter offers the opportunity of chemical composition imaging. Examples of these safe "X-Ray" inspections have been recently demonstrated on composition patterns of microchips. In a similar way, the strong absorption of water in biological and medical tissues can be used for tomographical mapping and can open a whole avenue of new techniques and devices.

In summary, THz radiation generated by short pulses offers an enormous potential for a multitude of technical applications. However, most of the applications require electrically driven devices with a widely frequency tuneable emission band. Still the development of pulsed THz sources driven by ultra short lasers will enable coherent spectroscopy of large objects in industry and medicine in all applications were costs are a secondary issue.

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