REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 10, 1998	9th Interim, December 1997 - February 1998

4. TITLE AND SUBTITLE

THz Radiation Source Trough Periodically Modulated Structures

5. FUNDING NUMBERS

C
N 68171-96-C-9015
R&D 7372-EE-01

6. AUTHOR(S)

E. Gornik, Ch. Rauch, G. Strasser, K. Unterrainer, W. Boxleitner

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Institut für Festkörperelektronik
Technische Universität Wien
Floragasse 7
A-1040 Wien, Austria

8. PERFORMING ORGANIZATION REPORT NUMBER

9th Interim Report

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

WK2Q6C-7372-EE01

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

19980410 104

13. ABSTRACT (Maximum 200 words)

We have shown that the quenching of the miniband states is independent of the direction of the applied bias for a 5 period superlattice. Experiments on a 10 period superlattice show that the transmission becomes asymmetric: enhanced for positive bias a and reduced for negative bias. This effect becomes more and more pronounced with increasing length of the SL. From a comparison of the calculated transfer ratio under the presence of interface roughness scattering, we are able to estimate the typical island sizes to be of the order of 10 nm.

Bow-tie structures are developed and optimized for the purpose of a broad band antenna in the range of THz frequencies. The optimized antennas are presently combined with small mesa structures for emission measurements. At present we have difficulties to couple the " large antennas" to the small 2µmx2µm mesas.

A population inversion in non-equilibrium plasmas can be achieved by driving a constant current through the plasma. Based on these ideas we have grown a set of structures where the plasma instability may be realized. The basic concept requires the realization of a large population inversion. The IV curves of the grown structures agree with the calculated IV curves. However from the IV curves it is not directly evident that a plasma instability is present. Therefore emission measurements, using a grid structure for coupling out of the light are under way to prove the existence of these instabilities which are expected to lead to strong THz emission.

14. SUBJECT TERMS

Carrier injection, quantum wires, THz sources, superlattice spectroscopy

15. NUMBER IF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

THz RADIATION SOURCE THROUGH PERIODICALLY MODULATED STRUCTURES

PROF. DR. ERICH GORNIK

INSITUT FÜR FESTKÖRPERELEKTRONIK
TECHNISCHE UNIVERSITÄT WIEN
FLORAGASSE 7
A- 1040 WIEN

CONTRACT NO. N68171-96-C-9015

9 th Interim Report

December 1997- February 1998

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Transmission through Superlattices with Interface Roughness

In the last report we reported the transmission of ballistic electrons through semiconductor superlattices (SL). These experiments could clearly resolve the quenching of the miniband states due to an applied electric field in good agreement with a calculation of the transfer ratio asuming only ballistic transport. While the quenching of the miniband states is independent of the direction of the applied bias, experiments show that the transmission becomes enhanced for positive bias applied to the receiving contact of the SL and reduced for negative biases if the superlattice exceeds a cetain lenght. This effect becomes more and more pronounced with increasing length of the SL.

In order to calculate the transfer ratio under the presence of scattering, we included interface roughness in our transmission calculation for a full three dimensional calculation. The interface structure has been obtained by a kinetic Monte-Carlo simulation producing typical island sizes of the order of 10 nm. We find an asymmetry in the calculated transmission with respect to the polarity of the bias if this type of interface roughness is included. Furthermore, the asymmetry strongly increases with the number of periods of the SL, while the transmission hardly depends on the total length of the superlattice. Both the shape of the transmission function and the length dependence are in good agreement with our experimental data (Fig. 1).

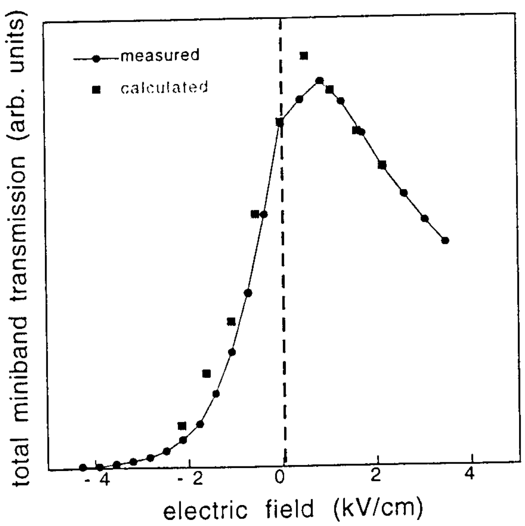

Figure 1: Miniband transmission vs. electric field. The experimental results (line) are compared to a calculation including interface roughness (squares)

The asymmetry can be explained in the following way: in a three dimensional structure the kinetic energy of an electron can be separated into a contribution E_z associated to a quasimomentum in the growth direction and a contribution $E_{||}$ with respect to the *x, y* direction. Without interface roughness, the z direction separates from the x, y direction. Therefore the transmission is strongly diminished, if the voltage drop causes an energy gain or loss along the SL which is larger than the miniband width D. Interface roughness destroys the translational invariance and therefore scattering transfers energy between E_z and $E_{||}$. If now a positive bias is applied to the collector, the energy gain of the electrons can be transferred to the x,y direction by scattering processes and the transmission becomes enhanced. Conversely, if a negative bias is applied, the electrons would need to gain energy from the || direction in order to gain kinetic energy against the field which is not possible since the injected electrons have $E_{||}$=0. Therefore scattering processes will reduce the transmission in this case. These effects become more pronounced for longer samples as the probability of an electron to perform a scattering process during the transmission increases with the length of the sample.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Mean Free Path of Ballistic Electrons in GaAs/AlGaAs Superlattices

The mean free path of ballistic electrons in a superlattice is measured using the technique of hot electron spectroscopy in magnetic fields perpendicular to the growth direction. We utilise the fact that the total effective path of an injected hot electron is a function of the applied magnetic field oriented perpendicular to the current direction.

A three terminal device is used to probe the transmission of undoped $GaAs/Ga_{0.7}Al_{0.3}As$ superlattices. An energy tuneable electron beam is generated by a tunnelling barrier and passes the superlattice after traversing a thin highly doped n-GaAs base layer and an undoped drift region. The collector current is measured as a function of the injection energy at 4.2 K. The probability for an injected hot electron to cross the superlattice reflects the transmission of the miniband under bias condition and can be considered to be proportional to the measured transfer ratio $a=I_C/I_E$.

Figure 2 shows the measured static transfer ratio for a five period superlattice versus applied electric field at different magnetic fields. While the electric field leads to the localisation of the electron wave function, the magnetic field increases the total path length of the electron in the superlattice, leading to a decrease of the measured transfer ratio. For magnetic fields above 1 Tesla, which corresponds to a total length of the electron path of about 80 nm, no coherent transport can be observed.

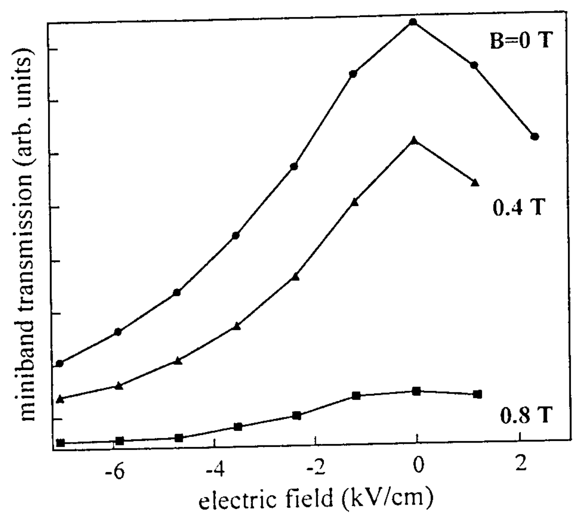

Figure 2: Miniband Transmission of a five period superlattice vs. electric field at different magnetic fields.

A detailed analysis of the miniband transmission gives us the coherence length and the scattering time of the electrons in the superlattice. The interface structure can only be obtained by a comparison to theory as discussed before. Island sizes of the order of 10 nm are suggested. Consequently we claim that the interface roughness is the limiting factor of the electron mean free path.

Bow Tie Antennas for THz Emission

A bow-tie structure is developed and optimised for the purpose of a broad band antenna in the range of THz frequencies. Theses antenna are coupled to the active mesa structure via airbridges in order to minimise parasitic capacitance.

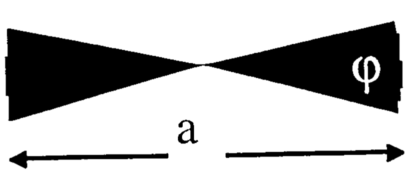

Figure 3: **Bow-tie antenna**

The impedance of an infinite bow-tie antenna depends only on its angle φ as shown inFig. 3.

$$Z = \frac{\eta_0}{2}\sqrt{\frac{1}{\varepsilon_{eff}}}\frac{K\left(\cos\frac{\varphi}{2}\right)}{K\left(\sin\frac{\varphi}{2}\right)} = \eta_0\sqrt{\frac{1}{\varepsilon_{eff}}}\frac{K\left(\tan^2\left(\frac{\pi}{4}-\frac{\varphi}{4}\right)\right)}{K'\left(\tan^2\left(\frac{\pi}{4}-\frac{\varphi}{4}\right)\right)} \quad (1)$$

where η_0 is the free-space impedance (377 Ohms), ε_{eff} is the effective dielectric constant. K(k) is the complete elliptic integral of the first kind, and $K'(k) = K((1-k^2)^{0.5})$.

For a finite antenna the dimension *a* equals one half of the maximum effective wavelength. The minimum effective wavelength is given by the smallest structures of the antenna. Between this two frequencies the impedance should be constant and given by equation 1.

For the frequency of interest (0.5 to 5 THz) we get

$$a = \frac{1}{2}\frac{c}{f_{min}}\frac{1}{\sqrt{\varepsilon_{eff}}} = 87\mu m$$

By changing the flare angle of the bow-tie antenna, we can choose the impedance to be equal to the impedance of the oscillator to get maximal radiation output or maximal electric output.The dependence of the impedance on the flare angle is shown in Fig.4.

If the oscillator is based on a negative differential resistance the theory predicts oscillations only if the absolute value of the negative differential resistance is greater than the impedance of the antenna.

For our experiments we choose three different values for the flare angel (20°, 60°, 150°) to get a possibility to check our results with theory.

Coherent Generation of Plasmons

Possibility of coherent plasmon generation (plasma instability) in quantum well structures with population inversion has been shown theoretically. The population inversion can be maintained by appropriate injection-extraction arrangements. Multi well structures, designed to sustain the population inversion and the plasma instability show I-V response consistent with calculations of the current density. These results suggest that this type of quantum well structures could be used as an active region to generate plasma oscillations, leading to radiation sources in the THz.

Non-equilibrium plasmas can develop spontaneously plasma oscillations. This can be viewed to be the result of plasma wave generation due to net downwards (in energy) single particle transitions, arising from the population inversion in the particle distribution. This population inversion can be, in principle, achieved by driving a constant current through the plasma. However, in solid state plasmas the velocity required to achieve the population inversion this way is prohibitively large, of the order of the Fermi velocity.

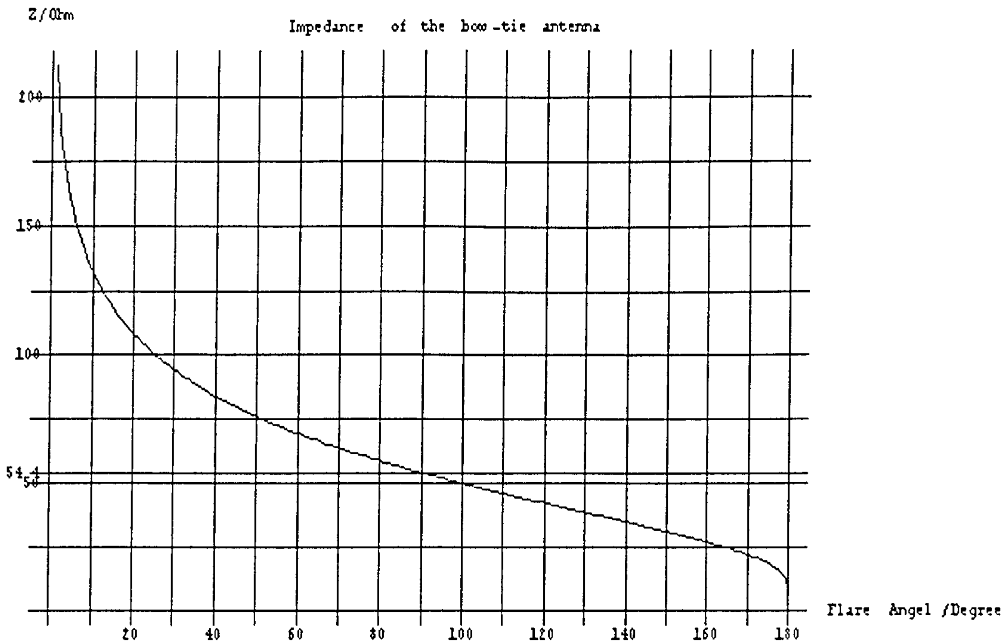

Figure 4: Impedance of the bow-tie antenna vs. flare angle

An alternative way to achieve population inversion is to use an energetically selective injection and extraction of carriers into a bounded active region where plasmons can be generated.

Based on these ideas we have developed a program to *design* mesoscopic structures where the plasma instability maybe realised and which can lead to generation of electromagnetic radiation. The basic concept behind sample g205 and g301 is to grow a region in which large population inversion can be achieved attached to a plasmon resonator.

Fig. 5 shows the current and conductivity characteristics of sample g301. The quantised states of the heterostructure can be clearly identified and are compared to a calculation of the static differential conductivity. The fit to the experiment gives us the occupation and life times of the resonant states.

A normal mode of the system occurs when the charge density oscillation response at a given frequency becomes large for arbitrarily small external perturbation. The sign of the imaginary part of the frequency dependent conductivity, indicates if negative, that the mode represents damped density oscillations (as a result of various losses in the system), and if positive it represents growing plasma oscillations (instability). When the electron-distribution is out of equilibrium, its excess energy can lead to an instability.

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

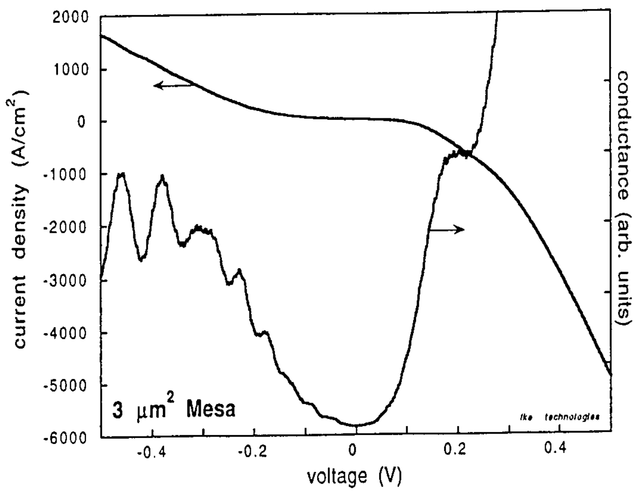

Figure 5: Current/Conductance vs. applied voltage for a $3\mu m^2$ Mesa.

From the IV curves it is not directly evident that a plasma instability is present. Therefore emission measurements, using a grid structure for outcoupling of the light are under way to prove the existence of these instabilities which are expected to lead to strong THz emission.