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TITLE: Observation of THz Oscillations and Efficient THz Emission from Contacted Low Temperature Grown GaAs Structures

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Observation of THz oscillations and efficient THz emission from contacted low temperature grown GaAs structures

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Abstract – **We have performed femtosecond differential transmission experiments in low temperature grown GaAs (LT-GaAs) layers under high electric fields. The fields were induced by voltages up to 60 V applied to interdigitated contacts with a few μm period. Up to about 10 oscillations of the field-induced transmission changes with a period of T = 2.2 ps were detected in a structure where the high-frequency effective length of the contacts was kept short. The large amplitude of the AC component of the differential transmission signal indicated that the amplitude of the light pulse induced oscillating electric field has to be of the same order of magnitude as the applied DC field. Thus the same has to be true also for the AC voltage between the fingers. In order to test this interpretation we have performed photomixing experiments. They yield a maximum emitted rf power of about 60 nW at a beat frequency of ν = 1/T = 0.44 THz, at only 10 mW of incident optical laser power. Computer simulations yield the same frequency for the contact structure considered as a microstrip patch antenna.**

I. INTRODUCTION

GaAs grown by molecular beam epitaxy (MBE) at unusually low temperatures (200 to 350°C) (LT-GaAs) exhibits, after suitable thermal annealing, both very short lifetimes for photo-generated carriers (down to the sub-ps range) and very high specific resistance (close to the value for intrinsic GaAs) [1-2]. These properties are attributed to fast recombination and/or capture of the photo-generated electrons and holes by a high density of deep traps. Due to these properties LT-GaAs has proven as a very promising material for efficient THz generation by photomixing [3-5]. In photomixers high DC fields are present in the active region between the contacts, which spatially separate electrons and holes close to the contacts. In order to investigate the influence of these fields on the relaxation and recombination kinetics we have performed fs differential transmission experiments on LT-GaAs layers with interdigitated metal-semiconductor-metal (MSM-) contacts as a function of applied DC bias. We have found two important results. First, we have observed a rather strong increase of the recombination or trapping times with increasing bias. This is, of course, an effect which negatively affects the performance of photomixers. Due to a decreasing recombination rate the DC component of the carrier density increases in comparison to the AC component. Therefore, the ratio of the THz component of the photocurrent to the (purely dissipative) DC photocurrent decreases accordingly. Secondly, however, we observed oscillations of the differential transmission signal with periods in the low ps range. These oscillations were particularly pronounced in sample structures with a large capacitance, which were specifically designed to contain a sufficiently large reservoir of charge to feed the photocurrent generated by the pump beam without causing a collapse of the applied voltage. From an analysis of the time-resolved transmission oscillations we have deduced an AC field amplitude which is of the same order of magnitude as the applied DC field, indicating that this sample structure should represent an efficient THz oscillator under photo-mixing conditions. Therefore, we have also performed photomixing experiments as a function of difference frequency of the two lasers. In fact, we observed a high efficiency for the emission of radiation at a resonance frequency of about 0.44 THz with a FWHM of about 12%. In order to understand these findings in detail and in order to further improve the design of the sample structure in the future, we have performed computer simulations of the device in terms of a micro-strip patch antenna. These calculations yield excellent agreement with the experimental findings.

In Section II of this paper we sketch the design of the sample. In Section III we report on the Differential transmission measurements. The results of the photomixing experiments and of the simulations of the antenna are described in Sections IV and V. We conclude with a brief outlook in Section VI.

II. SAMPLE

The 1.4 μm thick LT-GaAs layer was grown by MBE at 250 °C and annealed ex-situ at 600 °C for two minutes. Interdigitated Ti/Au contacts (finger width of 1 μm, finger length of 20 μm and finger spacing varying

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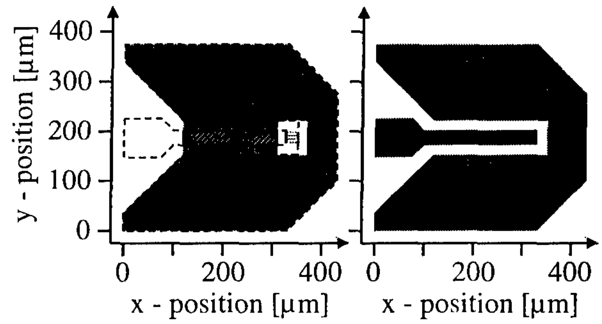

Fig. 1: Device structure. The left graph depicts the „bottom" Au layer, which also contains the interdigitated contacts (within the window). The upper layer, shown in the right part, is separated from the bottom layer by a 1μm thick polyimide layer. The latter one has an opening in the window region and the hatched area (see also text).

between 3 and 6 μm) and the „bottom contact layer" (depicted on the left hand side of Fig. 1) were deposited by photolithography and metal evaporation (200 Å Ti/1500 Å Au). Except for the interdigitated contacts and the hatched area shown in Fig. 1, the sample was covered by an approximately 1 μm thick polyimide layer. On top, another Ti/Au layer (200 Å/1500 Å) was deposited with the shape shown on the right hand side of Fig. 1. This way, a patch antenna is formed. The center stripe is connected to the „bottom contact layer" and to the left one of the interdigitated contacts on the LT-GaAs layer. The U-shaped part, which forms the „top contact layer", establishes the metallic connection to the right side of the finger contacts. The capacitor formed by the two Ti/Au layers with the polyimide layer as a dielectric ($\varepsilon = 4$) in between is 4.3 pF. 1150 Å of SiO_x, evaporated at the area with the intedigitated finger contacts, serve as surface passivation and anti reflection coating. Finally, the whole sample was removed from the substrate by the „epitaxial lift-off" technique [6] and glued onto a 0.2 mm thick glas substrate. For the epitaxial lift-off process a 50 nm thick „sacrificial" AlAs layer had been grown on the GaAs substrate prior to the growth of the LT-GaAs layer.

III. DIFFERENTIAL TRANSMISSION MEASUREMENT

The differential transmission experiments were performed with a mode-locked Ti-Saphire laser providing pulses with a FWHM of 100 fs at a repetition rate of 76 MHz. The photon energy hν of the pulses was tunable (simultaneously for pump and probe beam) from 1.4 to 1.5 eV, i.e. from below the band gap energy of GaAs (E_g = 1.42 eV at room temperature) to values substantially above. In Fig. 2 the relative transmission changes, measured at a photon energy of 1.43 eV = E_g + 10 meV (i.e. less than the thermal energy kT above band gap) taken for different applied voltages are shown as a function of the delay time of the probe beam. The density of electron hole pairs generated in the LT-GaAs layer by a single pulse was estimated to be about $2x10^{18}$ cm^{-3}. At zero volt the relative transmission ΔT/T increases due to bleaching of the absorption resulting from a high carrier density near the band edges. After reaching a maximum of 0.52 % the transmission signal decays with a time constant of about 700 fs. At finite fields there are two effects contributing to the transient transmission changes. First, the high fields induce heating of the electron hole plasma, resulting in a fast decay of the bleaching effect near to the band edge, which was very pronounced at zero volt. The second contribution is due to the Franz-Keldysh effect. At the photon energies used in this experiment the absorption decreases with increasing electric field. Therefore, a transient decrease of the electric field results in an increase of absorption and, hence, a transmission lower than in the dark case. A decrease of the electric field can be caused by internal screening due to mobile or trapped carriers, which become spatially separated by the electric field. But it can also originate from a break-down of the voltage at the finger contacts due to the high transient photoconductivity [7]. If the contacts are part of a resonant system (electromagnetic circuit or antenna) the latter effect will lead to (attenuated) oscillations of the field in the sample. This is exactly, what is observed in our device when a DC bias is applied (Fig.2). At increasing voltages the bleaching signal becomes more and more suppressed and the transient transmission signal is dominated by the Franz-Keldysh absorption. The AC component of this signal exhibits a voltage-independent period of about 2.25 ps. The decay of this component is significantly slower ($\tau_{AC} \approx$ 5 to 10 ps) than the decay of the DC component of the transient transmission changes ($\tau_{FC} \approx$ 3 ps), which reflects the time constant for return of the electric field in the sample to its original value in the dark state, when the photo-induced electrons and holes have disappeared due to extraction at the contacts or due to trapping or recombination within the LT-GaAs layer. The fact that the AC signal persists even after the DC signal has disappeared, its voltage-independent period and, last but not least, the large amplitude observed for the special design of this sample indicate that the potential between

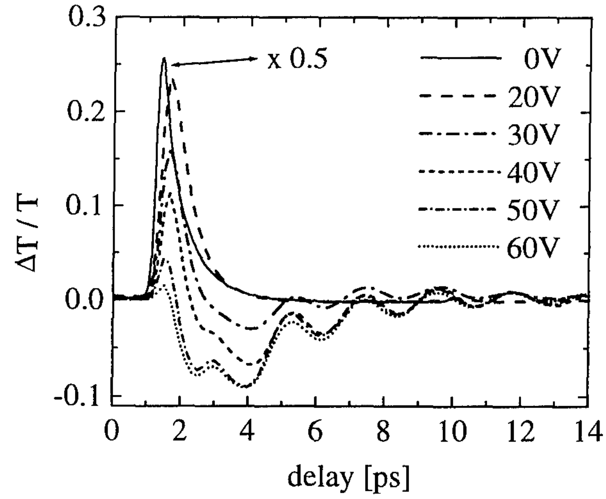

Fig. 2: Differential transmission at hν = 1.43 eV for U = 0, 20, 30, 40, 50, and 60 V. For U > 20 V the transmission signal exhibits an AC component with a period of 2.25 ps. (The curve for U = 0 is reduced by a factor 2).

the fingers performs (rather weakly attenuated) electromagnetic oscillations after each pulse.

In order to confirm this assumption we have tested the performance of our sample under periodic excitation conditions, as described in the following section.

IV. PHOTOMIXING EXPERIMENTS

The photomixing experiments were performed with a two color cw-Ti:Saphire laser [8]. With this system we are able to tune each color in the spectral range from 750 nm to 850 nm independently. We illuminate the device from the backside with a spot size of 15 μm. The generated THz radiation was focused with a teflon-lens onto a helium cooled InSb bolometer. The setup is described in detail in [9]. Fig. 3 shows the normalized power spectrum of the emitted THz radiation of the device in z direction (perpendicular to the plane of the metallizations). An electric field of 95 kV/cm was applied. The average incident optical intensity was 4.5 mW. We obtained a center frequency of about 0.44 THz and a line width (FWHM) of 54 GHz with a Lorentzian data fit. Assuming a $\delta(t)$-like excitation this corresponds to a damping constant of about 6 ps.

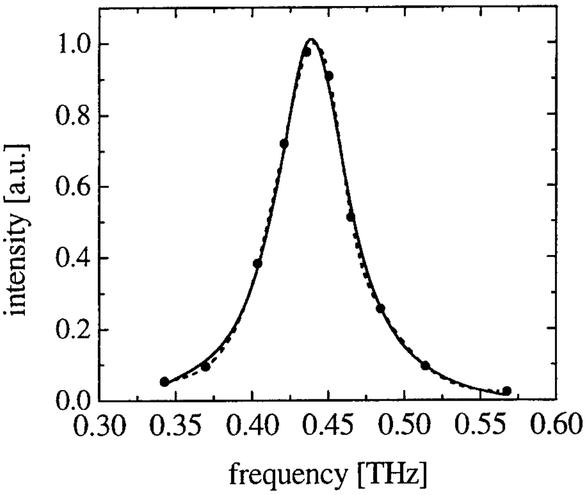

Fig. 3: Output power as a function of difference frequency. The full line depicts the Lorentzian fit.

At an incident optical intensity of 10 mW, we measured an output power of 60 nW. Considering reflection losses at the teflon lens we get an output power of 0.1 μW. Higher input intensities destroyed the devices glued on glass due to the poor thermal conductivity of the adhesive and the glass. Considerably higher output power should be achievable with devices attached to a heat sink.

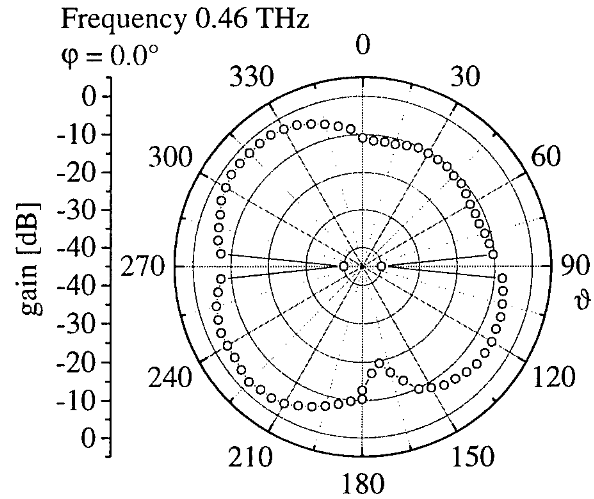

Fig. 5: Angular distribution of the calculated emitted power.

V. SIMULATION

We have also performed electromagnetic computer simulations for the structure. For the simulations shown here, the SONNET 6.0 software has been used, assuming a resistive active area around the interdigitated fingers. The open wall boundary conditions have been used for the antenna simulations. The radiation pattern has been calculated from the current distribution. In these simulations we obtain a resonant frequency of 0.46 THz, which is in excellent agreement with the measured values. Fig. 4 shows the current distribution of our device structure. The current in the top and bottom plates indicates that the device contact structure operates as a microstrip patch antenna. Clearly three extrema of the current density are observable in Fig. 4 in x-direction. The center finger is used for DC bias supply and therefore does not exhibit appreciable THz signal. The angular distribution of the radiated output power is depicted in Fig. 5. From this figure we expect a

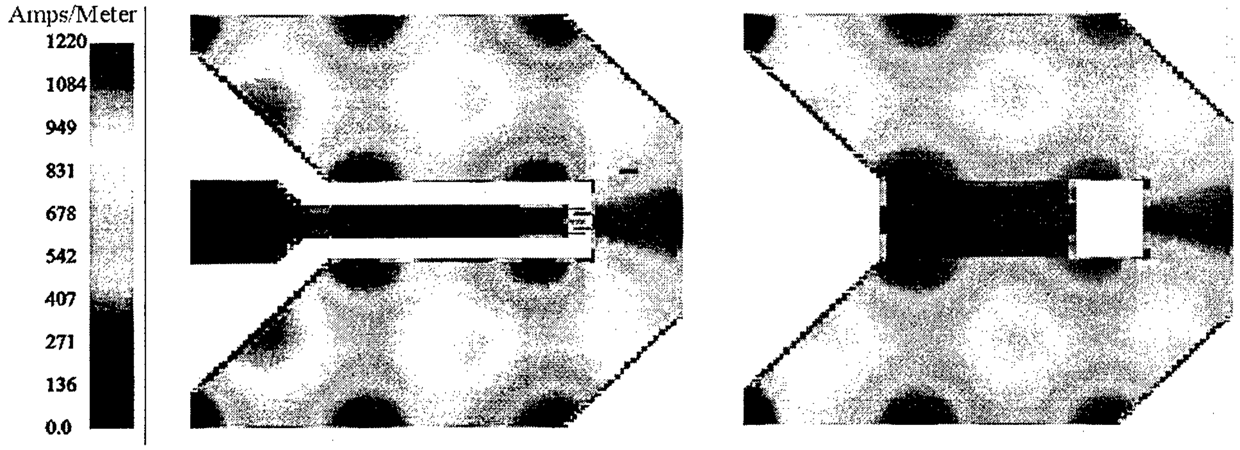

Fig. 4: Calculated current distribution of the device structure at the resonance frequency.

maximum output power in ±5/4π direction, respectively. However, our photomixing measurements above were taken at an angle of π/2. Hence, the measurements were not performed in the optimum configuration. Angle dependent simulations are in progress to test this assumption. From the simulated results we deduce that the device delivers higher output powers by at least a factor of 2 to 3 because of the radiation pattern.

VI. CONCLUSIONS AND OUTLOOK

Our pump & probe measurements, photomixing experiments and computer simulations yield efficient high-field oscillations at the same frequency of 0.44 THz for the investigated sample. We expect that the relatively high output power of the photomixer of presently 0.1 μW and the frequency can still be considerably increased by optimized design of the antenna structure, of the LT-GaAs material, and, in particular, by taking care of a better heat dissipation (no lift-off from the substrate, or attachment to a heat sink, e.g.).

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