Terahertz emission from electric field singularities in biased semiconductors

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We use electric field singularities in biased metal semiconductor microstructures to enhance the generation of terahertz (THz) radiation from semiconductors. We find that, regardless of the mechanism that is responsible for enhanced THz emission near the anode, singular electric fields near sharp anode features will enhance this emission by as much as an order of magnitude. We show scanning THz measurements of several of these structures and discuss the physical mechanism responsible for this enhanced emission. A new family of more efficient terahertz emitters based on these effects can be designed that will improve the dynamic range of THz imaging and spectroscopy systems.

Fast electrical transients and terahertz (THz) radiation are generated when biased coplanar strip lines (CPS's) or photoconductive switches are excited within the gap by short laser pulses. Krokel *et al.* realized that this generation process becomes particularly efficient when the excitation is carried out close to the anode.[1] This phenomenon was initially observed in CPS's fabricated on silicon on sapphire, but similar results were later observed in CPS's fabricated on a variety of substrates, e.g., low-temperature GaAs (LT GaAs), semi-insulating GaAs (SI GaAs),[2,3] doped GaAs substrates,[3] and InP.[3]

Several different models have been proposed to explain this peculiar generation mechanism near the anode in biased CPS's. These models were aimed mostly at explaining the aspects of ultrafast electrical pulse generation near the anode,[1,3,4] but some researchers also attempted to explain the efficient THz generation under similar conditions.[5] The spectrum of the phenomena that these models cover is broad: from local field screening by photogenerated carriers[3] to a trap-enhanced field near the anode in SI GaAs (Ref. 5; see Ref. 3 for a summary). Whereas some of these models tried to explain results obtained in large-gap CPS's (<50 μm), it was later shown that the same results can be obtained with smaller gaps (5 μm)

In this Letter we explore the emission of the THz radiation when short laser pulses excite biased photoconductive switches with anodes shaped in ways to enhance the electric fields acting on the photogenerated carriers. We achieve this by optimizing the geometry of the anodes in a way that maximizes the overlap between sharp anode features used to produce singular electric fields and the laser spot. The samples are fabricated by conventional lithography on LT GaAs grown at ~250 °C and later annealed at 600 °C for 1 min. The metal patterns are deposited by use of two different schemes for ohmic contacts on n–type GaAs (80 nm Au–Ge, 20 nm Ni, 20 nm Ti, 200 nm Au; 10 nm Ni, 80 nm Au–Ge, 20 nm Ni, 300 nm Au). These metallization schemes do not guarantee ohmic contacts to SI or LT GaAs. However, none of our structures exhibited nonlinear I–V curves as reported in a previous study of the positive electrode effect in metal–Si GaAs.[5] In fact, most of the I–V curves measured in our structures were linear and symmetric for fields smaller than 10 kV/cm. Also, the I–V curves did not exhibit the shape that is characteristic of two Schottky diodes connected back to back. All these findings do not preclude the formation of Schottky barriers at the metal–LT GaAs interface, but we believe that the results presented here are general.

The metal patterns usually consist of a pair of CPS's with sharp indentations of various shapes between them. We study the THz emission from such structures by using a standard coherent THz detection system with scanning capabilities on the emitter side. A short pulse (780 nm, 150 fs) from a mode-locked Ti:sapphire laser excites the sample through a 20× objective with a spatial resolution of ~2 μm. The samples are biased at various voltage levels (typically a few tens of volts, corresponding to fields up to 50 kV/cm). The generated THz radiation is then collected with a pair of off-axis paraboloids and focused on a THz dipole antenna fabricated on LT GaAs. This antenna is excited by another short laser pulse derived from the same Ti:sapphire laser. The emitter is then scanned two dimensionally, and we record the THz waveforms for each coordinate by scanning the delay of the beam that excites the antenna. We also performed zero-displacement electro-optic sampling[6] measurements in some of these structures.

Figure 1 shows a three-dimensional plot of the maximum THz emission from a sample with the geometry shown overlaid in the same picture. The metal electrodes consist of two strip lines with indentations separated by 70 μm. The sample is then biased at $V = 60$ V. Two observations are clear from this figure: (1) The THz emission at the positive electrode is more efficient by almost an order of magnitude than at the cathode; this is in perfect agreement with previous results.[2] (2) There is a clear enhancement of the THz

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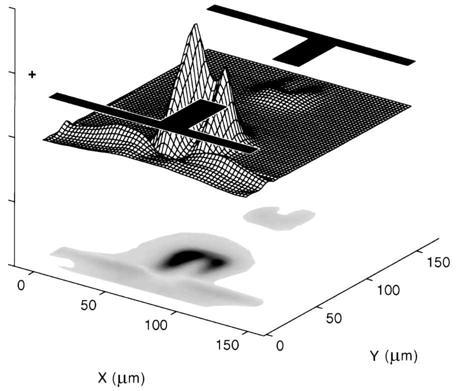

Fig. 1. Two-dimensional scan of the emitted THz radiation of the structure shown in solid black for a bias of 60 V. We obtain the data by scanning the sample and leaving all the optics fixed. Note the enhancement close to the corners of the anode.

emission when the laser beam excites areas that are close to the corners of the indentations, where the electric field is enhanced by geometrical effects. We then carried these studies one step further by varying the geometry of the indentations to increase the number of sharp corners and thus the magnitude of the singular electric fields that the photogenerated carriers will sense. THz scans for the anode vicinity in two of these structures are shown in Figs. 2(c) and 2(d). Diagrams of the corresponding metal structures are shown in Figs. 2(a) and 2(b), respectively. In these structures we replaced one of the rectangular indentations by one or two tips, respectively. These tips were then used as anodes and biased at the same voltage as used for Fig. 1(a). Again, a strong enhancement of the THz emission is observed when the electric field becomes singular because of the existence of sharp corners in the anode. We observed the same behavior for different bias voltages and gap distances between anodes and cathodes. We also investigated the dependence of these THz scans on incident laser power. Although there are some differences in the measured traces when the incident laser power is varied, the enhancement of the THz emission near singular electric fields is still observed when we reduce the laser power by more than 2 orders of magnitude. Zero-displacement electro-optic sampling measurements in these structures show that the corresponding measured electric fields are higher in the corners than in the other anode regions, with a ratio comparable with that observed in the scanned THz emission measurements.

One can gain some insight into the nature of the electric field enhanced THz generation mechanism by studying the dependence of the THz emission on the incident laser polarization. This dependence is shown in Fig. 3. The THz emission varies as $A + B\cos(2\phi)$, where ϕ is the angle measured from the [011] direction of the GaAs wafer. We carefully verified that this dependence was not due to diffraction effects by moving the excitation spot far away from the metal electrodes. This polarization dependence indicates that a large fraction of the THz emission is due to an instantaneous $\chi^{(2)}$ process[7], but from our data we cannot say what fractions of the THz generation are due to real carrier transport or to the optical nonlinearity. The nonlinearity that occurs under our experimental conditions is most probably field enhanced $\chi^{(2)}$. Hints of this were reported previously when second-harmonic generation was observed after a short pulse excited the area close to the positive electrode of a biased CPS.[8]

We solved self-consistently the three-dimensional electrostatics of the metal–semiconductor–metal structures, using an accurate modeling tool (PADRE),[9] and found that electric fields as high as tens of kilovolts per centimeter are present near the corners of the metal electrodes. These simulations do not take into account the time-dependent optical excitation. Inasmuch as the material parameters for LT GaAs (i.e., trap densities and cross sections, carrier concentrations and mobilities) are not known we opted to display the electric field profile for a device close to the one used in Fig. 1, assuming intrinsic GaAs

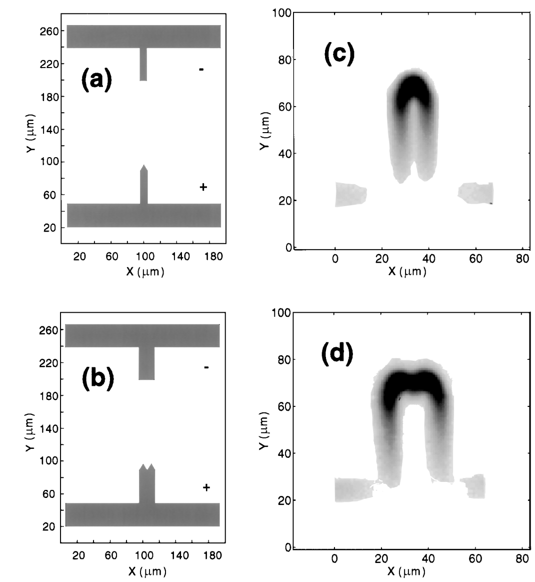

Fig. 2. (a), (b) Two new emitters with anodes designed to increase the overlap between the laser spot and the electric field singularities. (c), (d) The corresponding THz emission scans in the vicinity of the anodes.

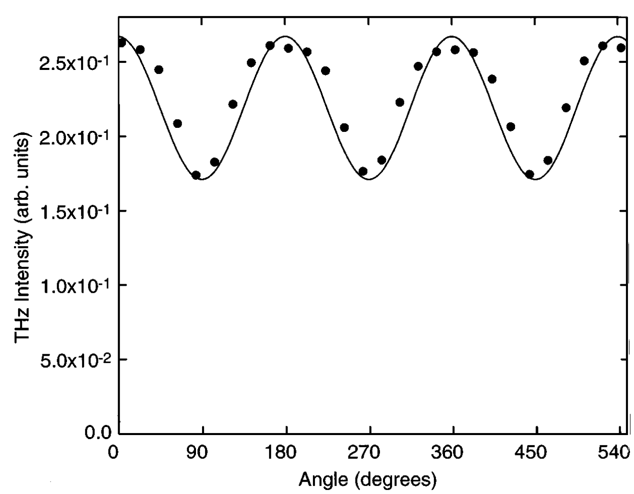

Fig. 3. Polarization dependence of the THz emission relative to the [011] axis of the GaAs wafer.

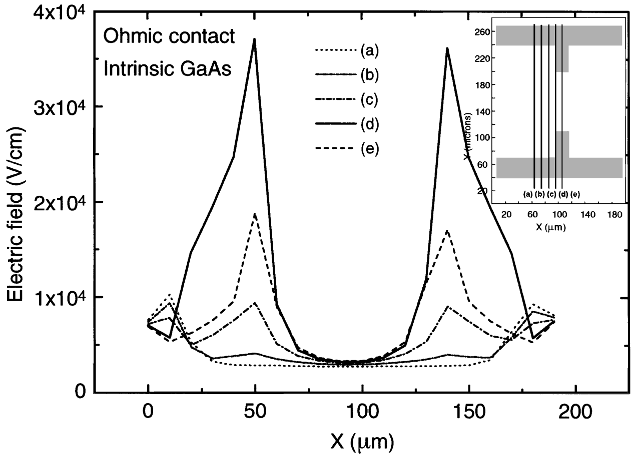

Fig. 4. Self-consistent calculation of the electric field close to the surface for a structure similar to the one used in Fig. 1 but with a 90-μm gap. The electric field is calculated along the lines shown in the inset and for a bias of 60 V.

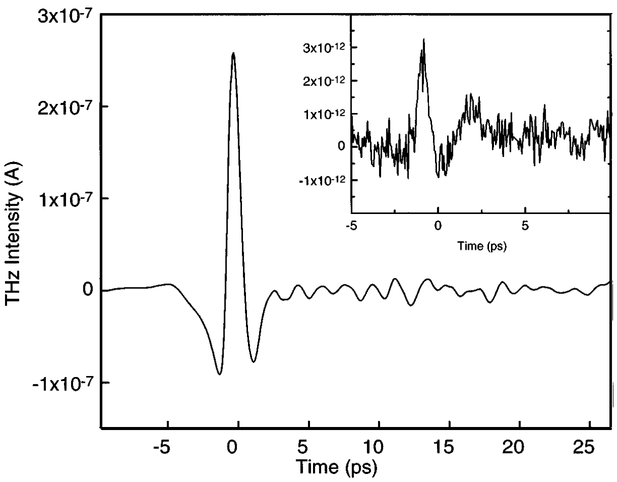

Fig. 5. High-intensity and low-intensity (inset) THz traces measured with lock-in detection with 30- and 300-ms time constants, respectively, showing nearly 6 orders of magnitude in dynamic range (or signal-to-noise ratio). The low-intensity trace is obtained by attenuation of the optical beam until the noise floor becomes visible.

and ohmic contacts. Obviously, these calculations (Fig. 4) do not model accurately the structures used in this research but rather are shown to illustrate the magnitude of the singular electric fields near sharp anode features. The increase in the electric field correlates qualitatively with our THz measurements, as shown by Figs. 1 and 2. We tried simulations with parameters closer to those found in SI GaAs, and for some sets of parameters we calculated stronger electric fields near the anode. It is possible that field enhancement relates to trap-enhanced electric fields, as was suggested earlier.[5] However, regardless of the mechanism responsible for enhanced electric fields near the anode, sharp anode features will enhance these electric fields (and hence the THz emission) even further, by as much as an order of magnitude.

Using these new optimized emitters and 50-μm-long LT GaAs dipole antennas, we were able to measure photocurrents induced by the THz emission of as much as 500 nA. Because the noise floor in a typical coherent-detection THz system is of the order of 0.1–0.2 pA,[10] this implies a dynamic range of 10^6. We achieved such a dynamic range by using a lock-in detection scheme and 70 (40) mW of optical power on the emitter (detector). A typical high-intensity THz trace is shown in Fig. 5. The inset shows a trace measured by weakening the optical beam so the noise level became visible. No particular effort was made to reduce the noise level in this weak-signal measurement. We believe that it is possible further to enhance the THz emission (and thus the dynamic range) beyond these results by designing other anodes that will optimize the overlap between sharp features and the focused laser spot.

In summary, we have shown that there is a significant enhancement of the THz radiation generation when emitters with sharp features in the anodes are used. We find that, regardless of the mechanism that is responsible for enhanced THz emission near the anode, singular electric fields near sharp anode features will enhance this emission by as much as an order of magnitude. The mechanism for the enhancement of the THz generation is a combination of carrier transport in high electric fields and field enhanced $\chi^{(2)}$. These emitters can improve the dynamic range of the THz imaging and spectroscopy systems beyond 10^6 or, alternatively, ease the laser power requirements for these systems.

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