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# Broadband Terahertz Emission from Ion-Implanted Semiconductors

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**Summary**. The terahertz radiation emitted from $Fe^+$ ion-implanted InGaAs surface emitters and InP photoconductive switches was measured. We experimentally observe an increase in the spectral width of terahertz radiation at greater ion damage, which we attribute to the ultrafast capture of photoexcited carriers. Results from a three-dimensional carrier dynamics simulation support this explanation.

## 1. Introduction

Single-cycle pulses of electromagnetic radiation, with spectra covering the far-infrared or terahertz (THz) range of 0.1-10 THz (3 mm-30µm), can be generated by the ultrafast separation of photoexcited carriers under an electric field.[1] The technique of terahertz time-domain spectroscopy relies upon the coherent generation and detection of such single-cycle pulses, and is proving useful in diverse areas of condensed matter physics.[2,3,4]

In order to increase the application of these emitters it is desirable to increase their spectral range. One method of decreasing the pulse duration (and thus broadening the spectrum) is to reduce the electric field decay time after excitation by using a defect-laden semiconductor. Such materials can be made either by low-temperature growth or via ion-implantation, and have sub-picosecond carrier trapping lifetimes and large carrier-defect momentum scattering rates.[1,5,6]

## 2. Sample details and experimental setup

A tandem accelerator was used to irradiate InGaAs, GaAs and InP samples with high energy ions. By choosing the incident ion species, energy and dose defects can be created with a certain depth distribution in a target. Multi-energy ion implantations were performed in order to create a uniform damage profile (Fig. 1) extending across the absorption depth of the semiconductor.[1]

The terahertz time-domain spectroscopy setup used was based on a 10fs Ti:Sapphire laser that outputs 400mW at a central wavelength of 790nm, and was similar to that described in Ref. 1. Chopping was performed electrically at 20kHz in the photoconductive switch emitter case, and optically at 2kHz for surface emitters. All measurements were taken at room temperature, with the terahertz path length under vacuum.

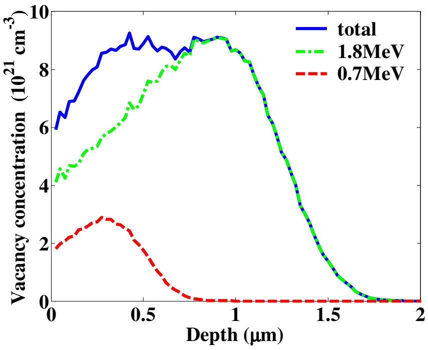


**Fig. 1.** The damage (vacancy) profile of $In_{0.53}Ga_{0.47}As:Fe^+$ calculated using the SRIM software (available at www.srim.org), extends over the absorption depth of 1.55μm photons (~1.3μm). Dual-energy (0.7 and 1.8MeV) implants of $Fe^+$ ions were performed at room temperature, for different ion doses. The highest dose for the 1.8MeV implant was $1\times10^{16}cm^{-2}$, and the other samples had 5% and 0.1% of this dose. The 0.7MeV implants had 28% of the corresponding 1.8MeV dose. For the $InP:Fe^+$ samples 2MeV and 0.8MeV implants were used, producing similar damage. A post-implantation annealing step (500°C for 30 minutes) allowed the resistivity to recover.

## 3. Measured and simulated terahertz emission

Figure 2a shows the measured THz electric field emitted from $InP:Fe^+$ photoconductive switches with 400μm gap, and biased by a 20kHz square wave at ±120V. The peak electric field decreases from $110Vm^{-1}$ to $7Vm^{-1}$

between the unimplanted and highest dose samples due to a reduced electron mobility. A higher ion dose produces electric field pulses with a shorter duration (Fig. 2a), and a broader spectrum (Fig. 2b). In the highest ion dose sample the trapping lifetime of photoexcited electrons (as measured by time-resolved photoluminescence) is 130fs, and is due to deep Fe-related acceptor defects.[5] A similar trend was observed in the THz emission from $In_{0.53}Ga_{0.47}As{:}Fe^+$ surfaces (Fig. 2c and d), where the carrier trapping time of the highest dose sample is of the order of 300fs.[6]

The terahertz emission from semiconductors can be accurately modelled using a three-dimensional carrier dynamics simulation.[7,8] By including an exponential decay in the number of photoexcited carriers damaged semiconductors can also be simulated.[1] The simulated electric field from InP photoconductive switches is plotted for carrier lifetimes of 100ps and 130fs in Fig. 3. Both the time and frequency domain results are qualitatively similar to those in Fig. 2a and 2b.

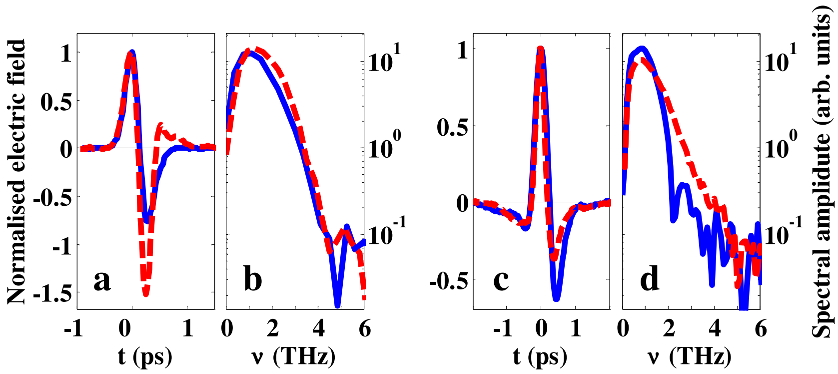


**Fig. 2.** **(a)** Normalised electric field versus time t from unimplanted InP (solid line) and $InP{:}Fe^+$ (dashed line) with an incident ion dose at 1.8MeV (0.7MeV) of $5\times10^{14}cm^{-2}$ ($1.4\times10^{14}cm^{-2}$). Measured using a 200μm <110> ZnTe crystal. **(b)** Spectra of a) as a function of frequency ν. **(c)** Normalised electric field from unimplanted $In_{0.53}Ga_{0.47}As$ (solid line) and $In_{0.53}Ga_{0.47}As{:}Fe^+$ (dashed line) with an incident ion dose at 1.8MeV (0.7MeV) of $5\times10^{14}cm^{-2}$ ($1.4\times10^{14}cm^{-2}$). The peak electric fields were $144Vm^{-1}$ and $20Vm^{-1}$ respectively. Measured using a 20μm <110> on 1mm <100> ZnTe crystal. **(d)** Spectra of c).

## 4. Conclusion

We observed a bandwidth increase with ion dose in $InP{:}Fe^+$ photoconductive switches, which offer benefits over GaAs based emitters in the spectral range 0-9THz owing to the higher TO phonon frequency of InP

(9.2THz, c.f. 8.1THz in GaAs). A similar bandwidth increase was seen from $In_{0.53}Ga_{0.47}As:Fe^{+}$ surfaces, which may be beneficial in terahertz systems based on 1.55μm wavelength lasers. The simulation results agree with the experimentally observed trend.

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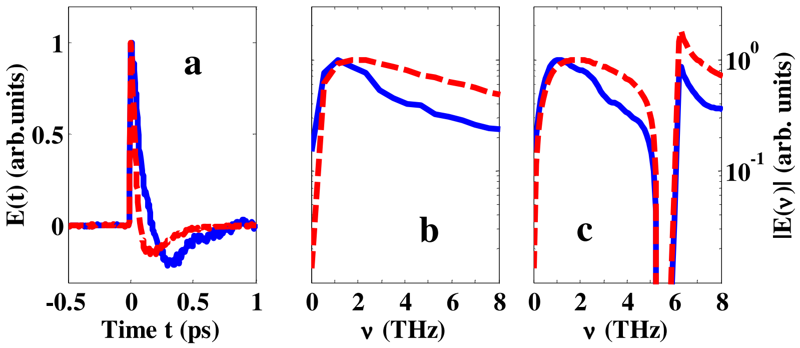


**Fig. 3. (a)** Normalised simulated electric field E(t) from InP photoconductive switches with a carrier trapping time of 100ps (solid line) and 130fs (dashed line). **(b)** Normalised spectra of a) as a function of frequency ν. **(c)** Normalised spectra from b) after including effect of 200μm ZnTe measurement crystal using a harmonic oscillator transmission function model with a TO (LO) phonon frequency of 5.3THz (6.2THz).

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