Photomixing and Photoconductive THz generation improvement in SI-GaAs after Carbon Irradiation

Prathmesh Deshmukh[1], Abhishek Singh[1], Sanjoy Pal[1], S. S. Prabhu[1], S. Mathimalar[1], Vandana Nanal[1],
R. G. Pillay[1], G.H. Doehler[2] , M. Mendez-Aller[3] and S. Preu[3]
[1]Tata Institute of Fundamental Research, HomiBhabha Road, Mumbai 400005, India
[2]Max-Planck Institute for the Science of Light, 91058 Erlangen, Germany
[3]Technische Universität Darmstadt, Rundeturmstr. 12, D-64283 Darmstadt, Germany

***Abstract*—We report significant improvement in pulsed and continuous wave (CW) THz generation when semi insulating GaAs (SI-GaAs) is irradiated with carbon ions. Irradiation reduces the carrier lifetime in SI-GaAs and increases its resistivity. This results in reduced screening effects and lesser heat dissipation in the THz pulse emitter. Reduced lifetime significantly improves the bandwidth of the CW THz system.**

I. INTRODUCTION

Frequencies in the range of 100 GHz to 10 THz are defined as the THz band of the electromagnetic spectrum. A lot of work is being carried out to generate frequencies in this region due to its potential application in the fields of biomedical, communication and spectroscopy [1-5]. Photoconductive emitters (PCE) are excellent sources for high power THz generation wherein the photoexcited carriers are accelerated in the presence of an external electric field. This is achieved either by exciting a PCE by a femtosecond laser to generate single cycle THz pulses or by CW photomixing, the latter proving to be a less expensive and more compact option due to availability of semiconductor laser diodes [6]. In this work, we irradiated SI-GaAs substrates with high energetic carbon ions, which can penetrate into the SI-GaAs up to ~2µm depth. The irradiation was done at 33 MeV energy and a gold foil was kept just before the sample to allow uniform distribution of ions inside the substrate. Irradiation generates a multitude of defects in the semiconductor wafer leading to a reduction in the carrier lifetime and an increase in the resistivity [7-8]. THz emission ability of irradiated material via photoconductive and photomixing technique is studied and compared to that of non-irradiated SI-GaAs.

II. DEVICE STRUCTURE AND IV CHARACTERISTICS

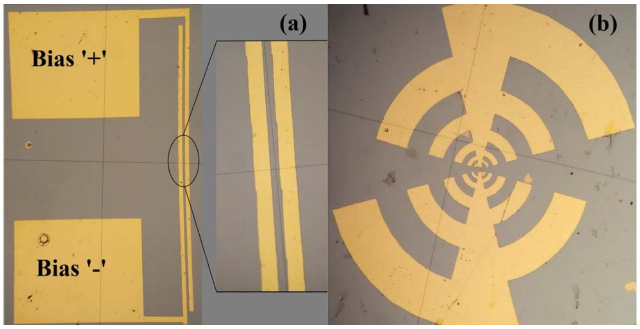


Fig.1 (a) Microscopic image of dipole antenna with 25µm electrode gap. The laser spot is focused in the central part shown. (b) Image of Log-periodic antenna.

A dipole antenna with an electrode gap of 25µm for photoconductive THz pulsed generation is shown in Fig 1(a). The laser spot is focused in the central part. A broadband, logarithmic-periodic antenna with standard 2µm interdigitated finger structures is fabricated for CW photomixing with as depicted in Fig 1 (b). Both antennas are fabricated on irradiated and non-irradiated SI-GaAs substrates using photolithography and E-beam lithography, respectively. Electrical contacts are made by gold wire bonding in case of dipole antenna and tungsten needles are used for log-periodic antenna. For good ohmic contacts, the CW samples were annealed at 410°C for 30 seconds.

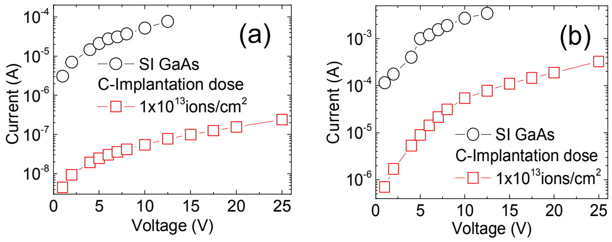
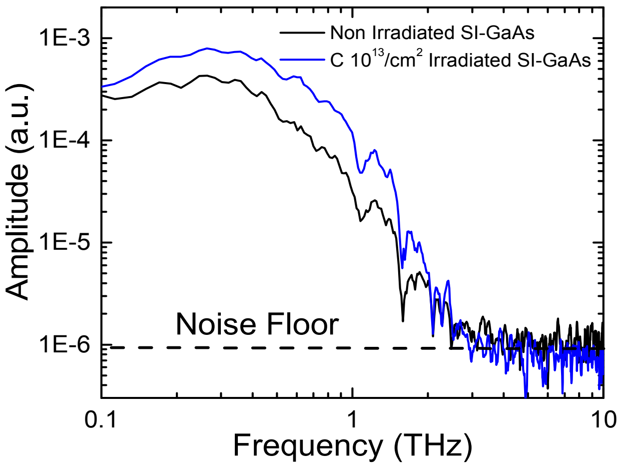


Fig.2 (a) Dark current-voltage characteristics without illumination for bare and irradiated SI-GaAs with a dose of 10^{13}ions/cm^2. (b) Same under 16 mW of optical illumination.

It is evident from Fig. 2 that the dark- and photocurrent drawn by antennas fabricated on implanted samples is ~3 to 4 orders and ~1.5 orders less, respectively, as compared to those on bare SI-GaAs, strongly reducing the heat generated within the device.

III. RESULTS

Carbon irradiation with an area dose of 10^{13}ions/cm^2 lowered the carrier lifetime to ~0.27 ps as compared to ~71 ps of non-irradiated SI-GaAs. THz pulse emission is studied using a THz-TDS setup with a 10 fs pulsed laser. At same applied bias (20 V for electrode gap of 25µm) and same optical excitation, irradiated SI-GaAs (~10^{13}/cm^2 dose) photoconductive emitter was ~ 3 times more efficient than usual non-irradiated SI-GaAs based emitter as illustrated in Fig. 3. This improvement can be attributed to lesser screening. Lower DC currents further facilitate application of higher bias voltages to devices on irradiated samples without thermal breakdown.



For CW photomixing, two 800nm CW lasers (TOPTICA) were used. The lasers are temperature tunable, such that their difference frequency can be adjusted from ~0.1 THz to ~1.17 THz by varying the temperature of the lasers.

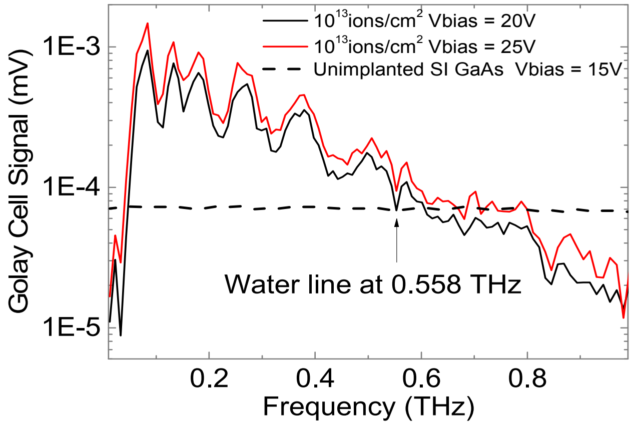


Fig.4. CW THz signal for Log-periodic antenna fabricated on 10^{13}/cm^2 implanted SI GaAs biased at 20V and 25V as compared to the heat signal detected from the non-irradiated bare SI GaAs.

Logarithmic-periodic devices were tested for THz emission efficiency using a Golay cell detector. The SI-GaAs devices draw a fairly high current of about ~2.7 mA even at a moderate bias of 10 V. The received power at 15 V is illustrated in Fig. 4. It shows a complete flat response vs. difference frequency of the lasers, as expected from a purely thermal signal by the heat generated within the device. Therefore, also the waterline at 558 GHz is not visible. Clearly, such a device is inappropriate for CW THz measurements. The 10^{13}/cm^2 ion implanted sample in contrast, shows a much lower photocurrent of ~190 μA even for an increased bias of 20V. The generated thermal noise is lower than noise floor of the Golay cell (The noise floor of the Golay cell is at level ~10^{-6} mV in Fig. 4 above). The mobility of the sample is enough to generate THz power for a spectral characterization from ~30 GHz to 1 THz, even with a fairly high NEP Golay cell. Maximum THz power of 60 nW was obtained when the device on 10^{13}/cm^2 was biased at 25 V.

Due to the high resistivity of the samples, we could not yet determine the carrier mobility by Hall measurements. Due to implantation damage, however, an improvement of the carrier mobility and the THz emission efficiency is expected by annealing the samples post ion irradiation to partially cure lattice defects for further optimization of the material parameters [9].

IV. SUMMARY

In summary, SI-GaAs was irradiated with carbon which reduces its carrier lifetime and increases resistivity. We have shown that ion implanted SI GaAs represents an efficient, inexpensive and simple to manufacture alternative to low temperature grown GaAs.

REFERENCES

[1] E. Pickwell and V. P. Wallace, “Biomedical applications of terahertz technology”, *Journal of Physics D: Applied Physics*, vol. 39, pp. R301, 2006.

[2] Masayoshi Tonouchi, “Cutting edge terahertz technology”, *Nature photonics*, vol. 1, p. 97, 2007.

[3] Thomas Klein-Ostmann and Tadao Nagatsuma, “A review on terahertz communications research”, *Journal of Infrared, Millimeter, and Terahertz waves*, vol. 32, pp. 143, 2011.

[4] Bradley Ferguson and Xi-cheng Zhang, “Materials for terahertz science and technology”, *Nature materials*, vol. 1, p. 26, 2006.

[5] P. Uhd Jepsen, David G. Cooke, Martin Koch, “Terahertz spectroscopy and imaging-Modern techniques and applications”, *Laser and Photonics Reviews*, vol. 5, p. 124, 2004.

[6] I. S. Gregory, W. R. Tribe, C. Baker, B. E. Cole, M. J. Evans, L. Spencer, M. Pepper, and M. Missous, "Continuous-wave terahertz system with a 60 dB dynamic range." *Applied Physics Letters*, vol. 86, p. 204104, 2005.

[7] Abhishek Singh, Sanjoy Pal, Harshad Surdi, S. S. Prabhu, Vandana Nanal, and R. G. Pillay, “Highly efficient and electrically robust carbon irradiated semi-insulating GaAs based photoconductive terahertz emitters”, *Applied Physics Letters*, vol. 104, p. 063501,2014.

[8] E. Castro-Camus, L. Fu, J. Lloyd-Hughes, H. H. Tan, C. Jagadish and M. B. Johnston, “Photoconductive response correction for detectors of terahertz radiation,” *Journal of Applied Physics*, vol. 104, p. 053113,2008.

[9] J. Mangeney, “THz photoconductive antennas made from ion-bombarded semiconductors,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 33, p. 455, 2012.