Proceedings Paper:

Mohandas, RA, Freeman, JR orcid.org/0000-0002-5493-6352, Rosamond, MC et al. (10 more authors) (2015) Generation of continuous wave terahertz radiation from Fe-doped InGaAs and InGaAsP. In: IEEE 2015 40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz). 40th International Conference on Infrared, Millimeter, and Terahertz Waves, 23-28 Aug 2015, Hong Kong. IEEE .

https://doi.org/10.1109/IRMMW-THz.2015.7327846

Generation of continuous wave terahertz radiation from Fe-doped InGaAs and InGaAsP

Reshma A. Mohandas[a], Joshua R. Freeman[a], Mark C. Rosamond[a], Siddhant Chowdhury[a], Lalitha Ponnampalam[b], Martyn Fice[b], Alwyn J. Seeds[b], P. J. Cannard[c], M. J. Robertson[c], D. G. Moodie[c], A.Giles Davies[a] , Edmund H. Linfield[a] and Paul Dean[a]
a) Institute of Microwaves & Photonics, University of Leeds, Leeds, LS2 9JT, United Kingdom
b) University College London, London, WC1E 6BT, United Kingdom
c) CIP Technologies, Adastral Park, Martlesham Heath, Ipswich, Suffolk, IP5 3RE, United Kingdom

***Abstract*—We demonstrate the generation of continuous wave terahertz radiation from Fe-doped InGaAs and Fe-doped InGaAsP photomixers grown by Metal Organic Chemical Vapor Deposition (MOCVD), using a pair of 1550 nm diode lasers. A bandwidth of > 2.4 THz is obtained from the emitters and the effect of doping on emitted power and bandwidth is studied.**

I. INTRODUCTION

THE non-ionizing and penetrative nature of terahertz (THz) radiation makes it ideal for numerous applications including biomedical imaging and security screening [1]. Various electronic and optical methods have been adopted for the generation of THz frequencies, both in the form of broadband pulses and narrowband continuous wave (cw) radiation. Of these methods, photoconductive emission is one of the most versatile, as it doesn't require the use of high power lasers for the generation unlike schemes based on non-linear optical processes.

Photomixers generate cw THz radiation by mixing two lasers on a semiconductor surface. The beating of these two laser fields produces a sum frequency and difference frequency, the latter of which modulates the semicondcutor conductance. The excited photocarriers are accelerated to metal electrodes under an applied bias, which gives rise to the emission of THz radiation via a suitable antenna structure. Such devices are robust, lend themselves to compact integration and also make use of widely-available lasers and components typically used in telecommunication networks. Furthermore, this generation scheme offers the possibility of wide tunability as well as narrow emission linewidths, the latter is derived from the linewidth of the excitation lasers.

Low-temperature-grown gallium arsenide (LT-GaAs) is widely employed for photomixing, due to its high resistivity (permitting a high bias to be applied), high mobility and sub-picosecond carrier lifetime (leading to large emission bandwidths). However, the bandgap of this material corresponds to ~800 nm, where diode laser and fibre technology is less developed. Because of this, there is significant motivation to develop photomixers that can be pumped with wavelengths ~1550 nm, corresponding to the well-developed telecommunication network bands.

Indium Gallium Arsenide (InGaAs) has a bandgap of ~1550 nm and has been used for the generation of broadband THz pulses in time domain systems [2]. InGaAs is usually p-type doped to compensate the high carrier concentration. Various methods have been adopted to improve the resistivity, including ion implantation, ion doping, low temperature growth and ion irradiation [3, 4]

Indium Gallium Arsenide Phosphide (InGaAsP) is a quaternary semiconductor that has been used widely for optoelectronic applications. The bandgap of InGaAsP lattice matched to InP typically corresponds to ~1300 nm, but in this work has been increased to match ~1550 nm by choice of material composition. Similar to InGaAs, InGaAsP is also an n-type material and can be doped with a p-type material to increase the resistivity.

In this paper we demonstrate the generation of cw THz radiation from both InGaAs and InGaAsP with Fe doping, grown by Metal Organic Chemical Vapor Deposition (MOCVD). The effect of doping on emitted power and bandwidth is studied.

II. RESULTS

In this work the Fe dopants are incorporated during MOCVD growth from a Ferrocene source. Alternatively, Fe dopants could be incorporated in to the InGaAs using ion implantation or ion irradiation. However, doping the InGaAs material with Fe using MOCVD offers a better surface quality, more uniform doping and less damage to the crystal structure. The pulsed THz emission from Fe-doped InGaAs (Fe:InGaAs) wafers has previously been demonstrated [3] and here we make use of the same layer structure, shown in the inset of Fig 2.

Two InGaAs and three InGaAsP wafers of different doping concentration were chosen for this study. The Fe:InGaAs wafer showed roughness on the surface, however the Fe:InGaAsP surface did not exhibit any increased surface roughness. The doping concentration was $1\times10^{16}\,cm^{-3}$, $9.5\times10^{16}\,cm^{-3}$ and $10\times10^{16}\,cm^{-3}$ for the three InGaAsP wafers and $0.5\times10^{16}\,cm^{-3}$ and $5.5\times10^{16}\,cm^{-3}$ for the two InGaAs wafers. The n-InP and n-InGaAs/InGaAsP layers acted as capping layers protecting the active layer from oxidation. After removal of the cap layers by wet chemical etching, a 3-turn self-complimentary logarithmic spiral antenna with an active region of 11.3 μm×11.3 μm was patterned on the device using electron beam lithography. The active region of the antenna contained 3 pairs of interdigitated fingers with a width of 0.2 μm and a gap size of 1.6 μm.

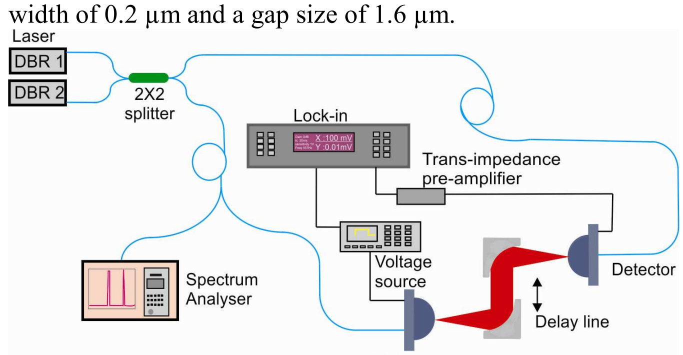

Fig 1: Experimental set-up for emitter characterization

The experimental set-up is shown in the Fig.1. Two distributed Bragg reflector (DBR), fibre coupled lasers emitting at ~1550 nm were used for excitation and detection. One of the lasers was kept at a fixed wavelength whereas the other laser was tuned to give a difference frequency in the range 0-2600 GHz. The output from each laser was coupled into two fibres using a 2×2 50:50 splitter; one output was fed to the emitter and the other was fed to the receiver. The emitter was biased with square pulses of 1 V amplitude at a frequency of 7.6 kHz. A hyper-hemispherical silicon lens attached to the substrate collected the THz radiation, which was focussed to the receiver using a pair of parabolic mirrors. A TOPTICA Photonics InGaAs receiver and mechanical delay line were used for coherent detection. The detected signal was amplified using a trans-impedance pre-amplifier and monitored using a lock-in amplifier referenced to the emitter bias.

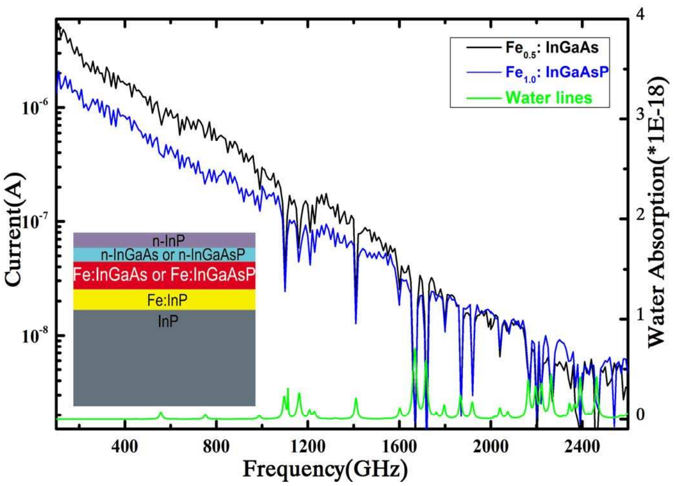

Fig 2: THz signal amplitude as a function of heterodyne frequency for an InGaAs and InGaAsP wafer with $0.5\times10^{16}\,cm^{-3}$ and $1.0\times10^{16}\,cm^{-3}$ Fe doping concentration respectively.

Figure 2 shows, the THz signal amplitude as a function of frequency for the low doped InGaAs and InGaAsP devices. The experiment was carried out in a non-purged environment and water absorption lines are also plotted to confirm the existence of signal at high frequencies where the signal level is low. In each case an emission bandwidth ~ 2.4 THz is attained. Nevertheless, the emitted power of the low-doped InGaAs device was higher compared to the InGaAsP device of similar doping concentration. This may be due to the higher absorption in the InGaAs wafer at ~1550 nm.

The emission bandwidths of the emitters were found to slightly decrease with increased doping, for example decreasing from ~2.4 THz to ~2.0 THz in InGaAsP, for doping levels of $1.0\times10^{16}\,cm^{-3}$ and $10.0\times10^{16}\,cm^{-3}$, respectively. In the case of InGaAs, increasing the doping from $0.5\times10^{16}\,cm^{-3}$ to $5.5\times10^{16}\,cm^{-3}$ similarly resulted in the bandwidth decreasing from ~2.4 THz to ~2.0 THz. Furthermore, the low doped devices were found to emit higher THz power compared to the high doped wafers for both InGaAs and InGaAsP. We attribute this to over compensation of the doping level leading to trapping of carriers before they reach the electrodes.

Figure 3 shows the THz signal amplitude as a function of emitter bias for the three different InGaAsP devices. All wafers were found to have a sub-quadratic dependence on the bias according to the equation $y = ax^b$. For b =1.65, the value of fitting co-efficient, a was found to decrease with doping, which can be explained by the higher carrier concentration in the low doped wafers.

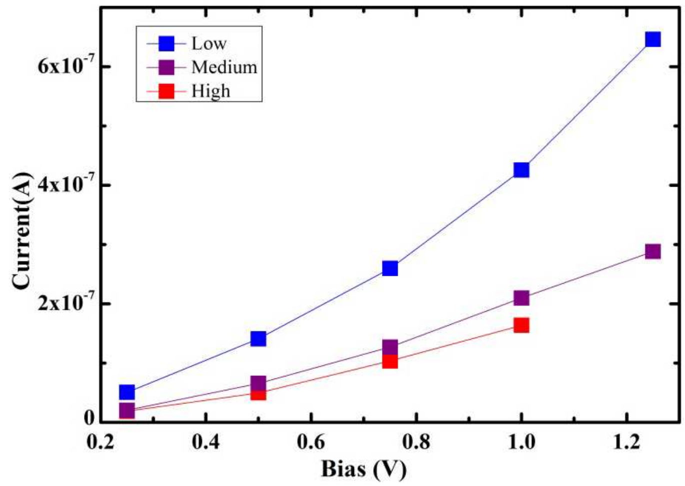

Fig 3: The signal amplitude with bias at 500 GHz for three different Fe doping concentrations in InGaAsP.

III. SUMMARY

A limited range of Fe doped InGaAs and InGaAsP wafers were used in this study, with doping levels in the range $0.5\times10^{16}\,cm^{-3}$ to $10\times10^{16}\,cm^{-3}$. The devices produced bandwidths up to 2.4 THz, in the case of InGaAs and InGaAsP with a doping concentration of $0.5\times10^{16}\,cm^{-3}$and $1.0\times10^{16}\,cm^{-3}$, respectively. It was found that the output power decreased with increased doping for both InGaAs and InGaAsP devices. Furthermore, smaller signal amplitudes were observed for InGaAsP devices compared to InGaAs devices with similar doping concentration, which we attribute to enhanced absorption at ~1550 nm in the latter.

IV. ACKNOWLEDGEMENTS

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) grant COTS (EP/J017671/1). We also acknowledge support from the ERC programme TOSCA; the Royal Society and Wolfson Foundation (AGD); and EPSRC Fellowships (PD, EP/J002356/1)

V. REFERENCES

[1] Ouchi, T., Kajiki, K., Koizumi, T., Itsuji, T., Koyama, Y., Sekiguchi, R., Kubota, O. & Kawase, K.. "Terahertz Imaging System for Medical Applications and Related High Efficiency Terahertz Devices". *Journal of Infrared, Millimeter, and Terahertz Waves,* 35**,** 118-130. July 2014

[2] Wood, C.D., et al., "Terahertz emission from metal-organic chemical vapor deposition grown Fe:InGaAs using 830 nm to 1.55 um excitation". *Applied Physics Letters*, 96(19): p. 194104-3.May 2010

[3]Martin, M. and E.R. Brown, "Critical comparison of GaAs and InGaAs THz photoconductors". *Terahertz Technology and Applications V* Proc to SPIE p. 826102-826102 March 2012

[4]. Mangeney, J., Merigault, A., Zerounian, N., Crozat, P., Blary, K. & Lampin, J. F. "Continuous wave terahertz generation up to 2THz by photomixing on ion-irradiated In0.53Ga0.47As at 1.55µm wavelengths." *Applied Physics Letters,* 91**,** 241102. December 2007