Ion-irradiated $In_{0.53}Ga_{0.47}As$ based photoconductive antennas excited at 1.55 µm for time domain terahertz spectroscopy

J. Mangeney, N. Chimot, L. Meignien, N. Zerounian, P. Crozat, K. Blary, J.F. Lampin, P.Mounaix

***Abstract*— We present a time-domain terahertz spectroscopy set up based on Er:fiber laser which delivers pulses at 1.55 µm wavelength and that integrates photoconductive antennas made on heavy ion-irradiated $In_{0.53}Ga_{0.47}As$ material as emitter and detector. A detailed study of the effect of the carrier lifetime on the terahertz signal characteristics has been performed. Improvements in bandwidth and in average power of the emitted terahertz radiation are observed with the decrease of the carrier lifetime on the emitter. The average power radiated is comparable with or greater than that emitted by similar low temperature grown GaAs photoconductive antennas excited by 780 nm wavelength optical pulses.**

***Index Terms*—Terahertz, Photoconductive materials, telecommunication systems, ultrafast semiconductor**

I. Introduction

The generation of coherent terahertz radiation from photoconductive antenna (PA) is an efficient way to reach the intermediate terahertz frequency range. The best terahertz performance is achieved by photoconductive antenna excited by ~0.8µm optical pulses and made from low-temperature-grown (LTG) GaAs material, because this material associates both subpicosecond carrier lifetime and high resistivity[1]. The use of a lower-bandgap semiconductor, such as $In_{0.53}Ga_{0.47}As$, allows cheap, compact and turnkey terahertz spectroscopy setups based on erbium fiber (Er:fiber) lasers, which can produce sub-picosecond pulses at a central wavelength λ=1.55 µm. Moreover, as the bandgap of the $In_{0.53}Ga_{0.47}As$ is smaller than the GaAs one, $In_{0.53}Ga_{0.47}As$ semiconductor shows a lower Γ-valley-effective mass which result in a higher electron mobility and greater terahertz power is expected[2]. We present a time-domain spectroscopy set-up based on Er:fiber laser which delivers pulses at 1.55 µm wavelength and that integrates photoconductive antennas made on heavy ion-irradiated $In_{0.53}Ga_{0.47}As$ material as emitter and detector. As carrier lifetime strongly influences the spectral distribution and the power of radiation emitted by PA[7-10], we investigated the effect of the carrier lifetime on the emitted terahertz signal characteristics.

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J. Mangeney, N. Chimot, L. Meignien, N. Zerounian, P. Crozat is [1]Institut d'Electronique Fondamentale, CNRS UMR 8622, Université Paris Sud, 91405 Orsay cedex, France (corresponding author: 33-1-69-15-75-50; fax: 33-1-69-15-40-90; e-mail: juliette.mangeney@ ief.u-psud.fr).

K. Blary, J. –F. Lampin, was with [2]Institut d'Electronique de Microélectronique et de Nanotechnologie, CNRS UMR 85200 , Cité Scientifique, 59652 Villeneuve d'Ascq cedex, France

P. Mounaix is with Centre de Physique Moléculaire Optique et Hertzienne, CNRS UMR 5798, Université Bordeaux I, 351 Cours de la Libération, 33405 Talence cedex, France

II. Samples

Undoped 1-µm-thick n-type $In_{0.53}Ga_{0.47}As$ layers were epitaxially grown by gas-source MBE on semi-insulating InP:Fe substrates. A mesa etching process was used to define $In_{0.53}Ga_{0.47}As$ absorbing area on the InP substrate. The layers were then irradiated by 11 MeV heavy ions (Br^+). Furthermore, a thin cap layer of optical transparent silicon nitride is grown to protect the device from oxidation and to provide an antireflection coating. The electrode patterns were fabricated by metal evaporation and a conventional lift-off photolithographic technique. Four $In_{0.53}Ga_{0.47}As$ emitters with carrier lifetimes of >1 ns, 4.2 ps, 0.7 ps and 0.3 ps were made by varying the ion irradiation dose from $4\times10^{10}cm^{-2}$ to $1\times10^{12}cm^{-2}$. The carrier lifetime in the detector was 0.3 ps.

III. Time domain measurements

In the time domain experiment, 250 fs optical pulses with a repetition rate of 14.3 MHz, delivered by a passively mode-locked fiber laser operating at 1550 nm were used to excite the emitter and the detector. Average optical power of 3 mw was incident on the emitter and on the detector. High-resistivity Si hyperhemispherical substrate lenses were attached back to the emitter and the receiver antennas.

For each emitter, a main positive peak is observed in Fig. 1, resulting from the ultrafast rise of the surge current by the photocarrier injection and the subsequent carrier acceleration under the bias field of the PC antennas. For the samples with picosecond carrier lifetimes, i.e. the ion-irradiated samples, the main positive peak is followed by a negative peak, attributed to the decay of the current governed by the carrier trapping. As the carrier lifetime decrease, the negative peak is more intense and happens earlier. Accordingly, in the spectral domain, the spectral peaks depend on the carrier lifetimes, being shifted to higher frequency when decreasing the carrier lifetime. The maximum of the spectrum is shifted from a frequency inferior to 0.05 THz for the un-irradiated $In_{0.53}Ga_{0.47}As$ PA to a frequency of 0.38 THz for the most irradiated $In_{0.53}Ga_{0.47}As$ PA ($1\times10^{12}cm^{-2}$).

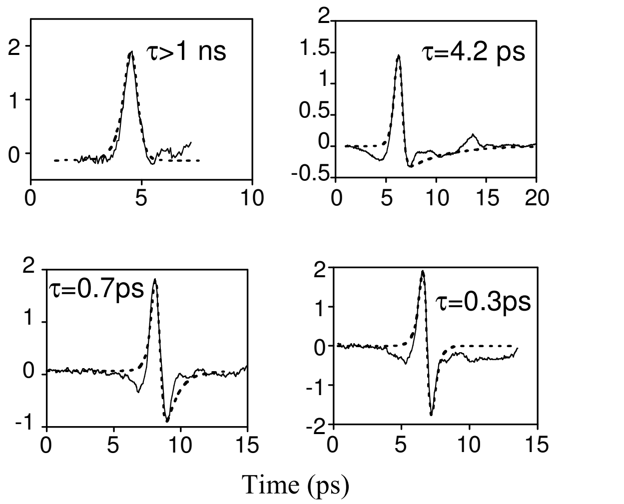

Figure 1 Terahertz radiation waveforms from Br+-irradiated $In_{0.53}Ga_{0.47}As$ emitters. The solid lines represent the measured waveforms and the dashed lines calculated waveforms using an analytical model based on charge transport [2].

IV. Time Integrated Measurements

Absolute terahertz powers emitted by the PA devices have also been investigated. The terahertz radiation was detected by a silicon diamond composite bolometer, located just in front of the Si lens placed on the back of the PA emitters. For these measurements, the $In_{0.53}Ga_{0.47}As$ PA devices were operating at their maximum possible bias voltage, which remains below the electric breakdown and also below the threshold for thermal runaway. The maximum bias voltages were 16V, 28 V, 40 V and 60 V for the samples with carrier lifetimes of >1 ns, 4.2 ps, 0.7 ps and 0.3 ps. Figure 2 represents the dependence of the radiated power on the incident laser power.

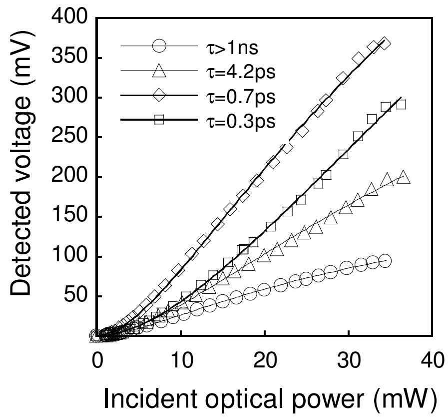

Figure 2 Bolometer output measured as a function of the average laser power driving the emitter for the photoconductive antennas with different carrier lifetime. The optical sensitivity of the bolometer is 4.6 10^5 V/W (included preamplifier gain).

The maximum achieved power of 0.8 µW is delivered by photoconductive antennas having 0.7 ps carrier lifetime. The increase of the terahertz powerwith the decrease of the carrier lifetime, observed in Fig. 2, is attributed to the strong increase of the maximum possible bias voltage. For PA with 0.3 ps carrier lifetime, the decrease of the radiated power is due to the carrier recombination that occurred before the end of the optical pulse. The performances of these ion-irradiated $In_{0.53}Ga_{0.47}As$ PAs have been directly compared to those of a typical LTG GaAs antenna, having a carrier lifetime of ~ 1 ps, by measuring the delivered terahertz power in the same experimental set up and with the same calibrated bolometer. The power delivered by the LTG GaAs PA biased at 60 V and excited by optical pulse trains of 36 mW average optical power at 780 nm central wavelength was 0.47 µW, in agreement with the measured powers reported by other group [4]. The terahertz powers emitted by ion-irradiated $In_{0.53}Ga_{0.47}As$ PA excited by 1550 nm optical pulses are then comparable with or greater than that emitted by LTG-GaAs PA excited by 780 nm optical pulses.

Figure 3 shows the radiated power as a function of the carrier lifetime in $In_{0.53}Ga_{0.47}As$ PA, computed for different frequencies from time domain measurements with Bolometer detector normalization. The increase of the radiated terahertz power with the decrease of the carrier lifetime at high frequency has important practical implications for terahertz emitter design: the carrier lifetime of the emitter can be adjusted to reach a specific terahertz spectral range.

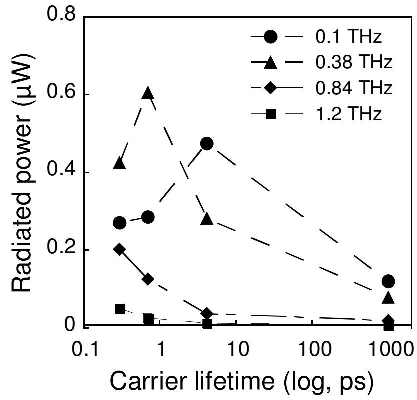

Figure 3 Emitted terahertz power as a function of the carrier lifetime at 0.1 THz (circle), 0.38 THz(triangle), 0.84 THz (diamond) and 1.2 THz (square) computed from time domain measurements with bolometer detector normalization.

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