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FREQUENCY DIFFERENCE GENERATION IN THE TERAHERTZ REGION USING LTG-GaAs PHOTODETECTOR

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Abstract-We demonstrated Terahertz generation by optical frequency difference with a continuous tuning between 0.2 (~ 1 µW) and 3 THz (~1 nW). To this aim, high speed photodetectors with an interdigited photoconductor scheme on a submicron scale, loaded by THz log-periodic antennas, were deposited on a 1 µm-thick Low Temperature Grown (200 °C) GaAs epilayer. Two Ti:Sapphire laser beams (~ 30 mW) focused onto the device yield Terahertz radiation collimated through Silicon lens and detected by means of lock-in bolometer detection. The generated power and frequency, consistent with semiconductor and circuit time constants, are discussed in the prospects of antenna arrays and optical cavities.

Key words: Terahertz, photomixing, LTG GaAs

I INTRODUCTION

Optical generation in the Terahertz gap by photomixing [1]-[3] of two Ti:Al_2O_3 or semiconductor lasers was made possible owing to the remarkable properties of Low Temperature Grown (LTG) Gallium Arsenide [4]-[5]. Such a semiconductor, grown at typical temperatures between 180 °C and 250 °C under non stoichiometric conditions, exhibits a large number of defects, often in excess of 10^{19} cm^{-3} in such a way that charge carriers, created by photoexcitation, are rapidly trapped, in most case at subpicosecond scale. As a consequence, the mobility lifetime of photoexcited electrons in the conduction band is extremely short blocking any photoconductivity process inside the sample.

Basically, the photomixing experiments aforementioned rely on the energy detection principle of a fast photodetector. The fact that the response is proportional to the square of the incident electric field enables the generation of frequency difference component when two optical beams, with a frequency offset, are impinging the sample. The intermediate frequency component, to use the terminology of heterodyne systems, is subsequently converted into a Terahertz radiation via radiating elements, such as dipole or slot antennas which are either broadband or resonant at a certain frequency.

It was early recognized that the frequency dependence of the conversion between the optical beams and the Terahertz radiation was governed by two time constants. Firstly, the life-time of the photoexcited carriers which is an intrinsic property of the active layer of the photodetector. On the other hand, owing to the utilization of an optoelectronic device instead of a full optical device, some extra circuit limitations have to be taken into account. On this basis the key figure of merit was the RC time constant of the circuit constituted by the photodetector and the Terahertz antennas.

In this paper, we show the possibility to use such a principle to down-convert two optical signals around 800 nm at an intermediate frequency in the far infra-red spectrum. One of the laser was continuously tuned so that an optically monochromatic tunable source can be fabricated. The output power achieved in the present work compares with the best data published in the literature under the same broadband conditions. They also fit reasonably the expected frequency dependence on the basis of RC and life-time constants. The analysis is supported by material-based experiments such as X-Ray rocking curve and time resolved photoreflectance carried prior to the conversion experiment on the LTG GaAs samples, reported in section II. Design rules and fabrication techniques are explained in section III while the frequency and voltage dependence along with some prospects and concluding remarks are given in section IV.

II LOW TEMPERATURE GROWN GaAs EPILAYER

The epitaxial material used for all the experiments was grown by Gas Source Molecular Beam Epitaxy. Starting from a Semi-insulating (100) GaAs substrate, a buffer layer was firstly grown at the nominal temperature of 600 °C followed by the growth of a 1 µm thick LTG GaAs with in situ control by RHEED diffraction pattern. For the LTG layer, the growth temperature was around 200 °C estimated via a thermocouple. All epilayers are nominally undoped. The samples were not annealed.

In order to assess the arsenic excess concentration of the capping LTG layer, X-Ray diffraction patterns were systematically recorded for all the samples. Figure 1 displays a typical X-Ray rocking curve. Two peaks due to the Bragg reflection are shown.

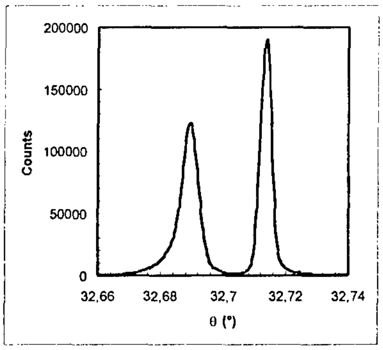

Fig. 1 X-Ray Rocking curve of the sample grown at 200 ° C

The main peak at 32.714° corresponds to the substrate and buffer layers whereas the satellite one at 32.69 ° is characteristic of the LTG epilayer with a large number of Ga antisites (As_{Ga}). The mismatch ($\Delta a/a$) between the substrate and the non-stoechiometric LTG GaAs was 6.5×10^{-4}. It was previously shown [6] that the determination of this mismatch could also be used for estimating the number of defects. Following this approach for the present technology, we found 5×10^{19} cm^{-3}. Also, the defects characteristics in LTG GaAs can be compared to those of EL2 defects and such a finding can be useful to have a first estimate of the capture time (τ) within the semiconductor which is a key figure of merit as discussed above. With a typical value for the cross-section of 5×10^{-14} cm^{-2} and a thermal velocity of 10^{7} cm/s we calculated $\tau = 400$ fs.

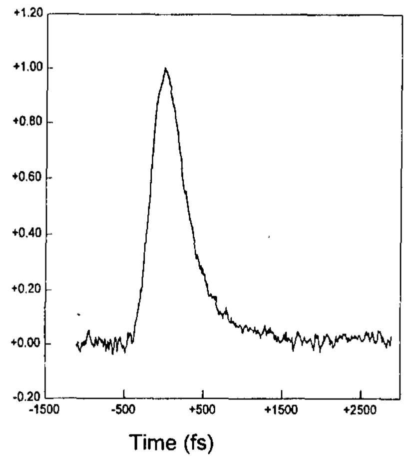

Fig. 2 Time resolved photoreflectance

Experimentally the capture time, which can be compared to a mobility lifetime, was measured by means of time-resolved photoreflectance measurements [7]-[9]. These experiments were also performed at IEMN laboratory. A typical time dependence of the reflectivity signal is given in Figure 2. For this experiment, 100 fs optical pulses near 800 nm were used with a repetition rate of 78 MHz. After a steep increase in the reflected signal in accordance with the build-up time of the optical pulse, an exponential rolloff is observed with a short time constant in the 500 fs scale.

III DESIGN AND FABRICATION

The design of the fabricated devices relies first of all on the calculation of the photodetector and then of the radiating antenna. For the former, the guidelines are the achievement of a low capacitance level so that the RC time constant of the overall system can be kept as low as possible while maintaining a reasonable transit time with respect to the photocarrier life-time. These considerations have motivated the choice of an interdigited scheme on a submicron scale. On the other hand, shadowing effects by the metal fingers have also to be alleviated. To satisfy the corresponding trade-off we thus decided to implement a nominal pattern consisting of 0.2 µm -width finger with an interspacing of 1.8 µm. Figure 3 is a Scanning Electron Micrograph of this pattern after the metallisation stage. With this geometry the capacitance (8x8 μm^2) of the photodetector can be calculated by means of the model published in reference [10]. A value of 0.4 fF is representative of such a technology.

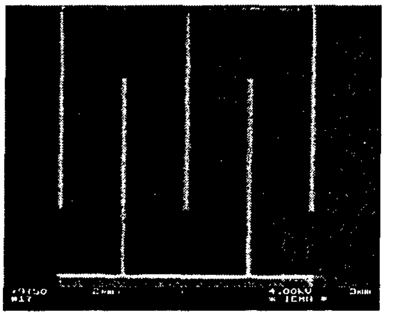

Fig. 3 SEM of the interdigited capacitance scheme

The second stage in the design was dealing with the radiating elements. As discussed in introduction either a broadband or a resonant antenna can be chosen depending on the targeted project. For the present work aimed at assessing a broadband source, we have designed log spiral antennas. In practice, the design was carried out by means of Momentum and High frequency Structure Simulator by Hewlett Packard [11]. The outcome is the input impedance, which permits one to assess the circuit time constant as a function of frequency.

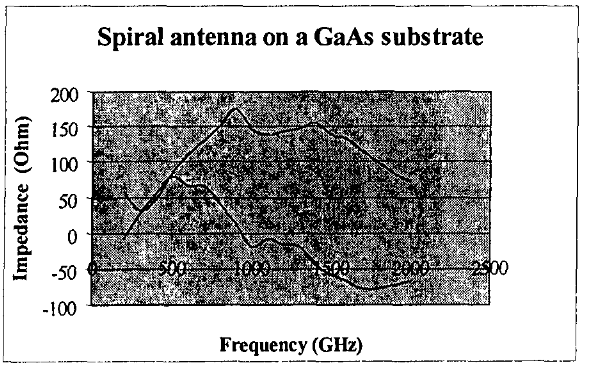

Fig. 4 : Real and Imaginary part of the log-spiral antenna impedance as a function of frequency

Starting from the epitaxial material outlined in section II, the fabrication of the devices was made by combining e-beam patterning (LEICA HR PG) and photolithography techniques. The former was required to write, in electron sensible resist (PMMA), the mould for subsequent metallisation. Conversely, photolithography was used for patterning the antennas, which necessitates a large portion of the wafer. Metallisation was made by evaporation with a 50 nm-thick Ti/300nm-thick Au metal contact. Despite the fact that the LTG layers were non-intentionally doped with non-annealing processes, let us recall that the metal/semiconductor contacts deposited on LTG are ohmic. Figure 5 is a scanning electron micrograph of the completed device with a zoomed view of one of the photodetectors in inset.

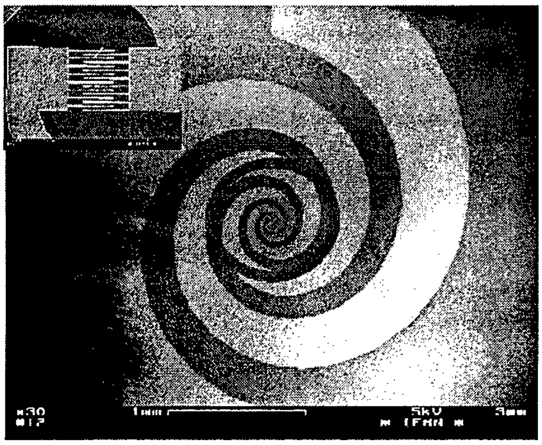

Fig. 5 SEM of the devices including the log periodic antennas

The last stage in the fabrication consists in mounting the half-size wafer onto a dielectric substrate in order to interconnect the devices to bias pads.

IV RESULTS

A schematic overview of the THz photomixing generation experiment is shown in Fig 6. Two CW Ti: Sapphire lasers (899-29 Autoscan, Coherent Inc.), tunable from 700 to 810 nm and 790 to 910 nm, were both pumped by a 23 W Argon laser. For the present demonstration, the wavelength of the two lasers was around 800 nm. A half wave plate and a polarizer were used to adjust carefully lasers pump power. Two laser beams were spatially overlapped by a beam splitter and focused by a lens onto the THz photomixer. THz emission was precollimated by the Silicon lens attached on the back side of the chip and focused with a parabolic mirror onto a Ge bolometer which operates at 4.2 K. The output signal from the detector was fed to a lock-in amplifier.

The Terahertz beam is preferentially radiating in the substrate due to the difference in the permittivity constants between air and the semiconductor. The trapping within the substrate is however avoided by the high resistivity Silicon hyperhemispherical lens (Diameter 10 mm).

Special attention was paid to the alignment of the various elements notably the silicon lens which was mounted on the backside on a X,Y,Z translation stage. For the measurement of the absolute power we have used the calibration factors given by the manufacturer.

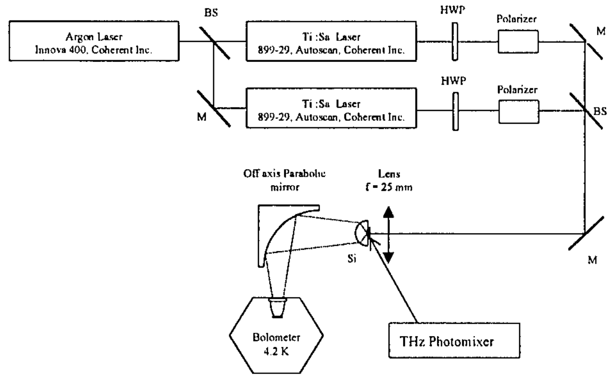

Fig. 6 Experimental setup of a tunable coherent cw – THz radiation system, HWP : Half Wave Plate, BS : Beam Splitter, Si : Collimating hyperhemispherical Silicon Lens

The first step for the experiment was to record the dark and photo currents as a function of bias voltage. It should be emphasized that the LTG samples were not annealed. Generally such a thermal treatment is used for forming Arsenic precipitates improving dramatically the resistivity of the sample. In counterpart a degradation of the life-time can be pointed out at the detrimental of the frequency capability. The ratio between the dark and photocurrent was found in excess of 10:1, with typically a photocurrent of 125 µA at 9V.

Then, we have recorded the detected voltage of the bolometer at various bias voltages. As expected a quadradic relation ship was found in accordance with early experiments.

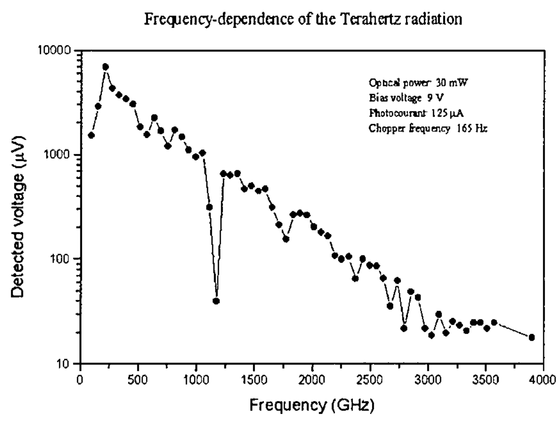

Fig. 7: Frequency-dependence of the Terahertz radiation

At last, we have systematically changed the frequency of one of the laser. Owing to their remarkable purety (500 kHz) and stability, the frequency difference (intermediate frequency) was weakly fluctuating with time so that confident data can be measured without the requirement of an external stabilization. Figure 7 shows the detected voltage on the lock-in detection plotted in semi-logarithmic scale as a function of frequency. By translating this voltage information in terms of radiating power (10 kV/W) we obtained about 1 μW in the lower part of the submillimeter wave spectrum and about 2 nW at 3 THz. This results compare with those obtained by the MIT group [12]–[13] under comparable conditions.

The typical optical power impinging the photodetector was about 30 mW. For higher optical levels, saturation can be observed and hence no benefit in terms of delivered power. Further improvements can be expected using the high pump power capabilities of the two autoscan lasers (500mW). On this basis it could be useful to envisage an array of broadband antennas in a fashion similar to that employed for high power amplification or source systems.

Another way of improvement concerns the use of optical cavity such as those which are widely used for photodetectors. Indeed, the efficiency of the photodetector is mainly limited by the very shallow high electric field layer despite the fact that carrier absorption takes place within a 1 μm depth. Such a limitation was recently recognized for high speed photomixer [14] and could be implemented via membrane-like or microcavity devices.

As a last point, the recent work about the absorption of LTG material below the gap permits one to consider the operation of the devices at long wavelengths (1.3 and 1.55 μm)[15].

CONCLUSION

High-speed interdigited photodetector loaded by broadband log spiral Terahertz antennas were fabricated on a Low Temperature Grown GaAs epilayer. By tuning continuously the difference between two Ti:Sapphire lasers it was shown the possibility to generate a Terahertz signal with high spectral purity and significant power.

Numerous degrees of freedom still exist for further improving the results notably with the implementation of an array of antenna or of optical cavities.

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