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# Terahertz generation and power limits in In<sub>0.53</sub>Ga<sub>0.47</sub>As photomixer coupled to transverse-electromagnetic-horn antenna driven at 1.55 $\mu\text{m}$ wavelengths

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# Terahertz generation and power limits in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ photomixer coupled to transverse-electromagnetic-horn antenna driven at $1.55 \mu\text{m}$ wavelengths

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We report continuous wave generation at frequencies up to 2 THz using ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixers coupled to transverse-electromagnetic-horn antennae driven at  $\sim 1.55 \mu\text{m}$  wavelength. Output powers up to  $0.1 \mu\text{W}$  at 700 GHz have been achieved. The dependence of the output power on incident optical power and the bias voltage is analyzed in the both regimes of Ohmic transport and recombination-limited transport. The fundamental limitations of the performance of the photomixer devices based on photoconductive phenomenon in recombination-limited transport are analyzed.   2010 American Institute of Physics. [doi:10.1063/1.3505341]

Photomixing is a useful technique for generation and detection of tunable terahertz (THz) radiation, offering large scanning bandwidths and good signal-to-noise ratios.<sup>1</sup> The most successful photoconductive-based photomixers demonstrated to date have been made with low temperature-grown GaAs or ErAs-GaAs materials.<sup>2,3</sup> Coupled to broadband planar antennae, output powers up to  $3.5 \mu\text{W}$  at 700 GHz have been reported using two lasers operating at  $\sim 800 \text{ nm}$  wavelengths. Recent studies have demonstrated an improvement of the available power at 700 GHz by coupling photomixers with an integrated transverse-electromagnetic-horn antenna (TEM-HA).<sup>4</sup> There is a strong interest to shift the operating wavelength toward  $1.55 \mu\text{m}$  to benefit from mature telecom-based technology,<sup>5,6</sup> which offers compact, low cost optical amplifiers and semiconductor lasers. Photomixers for operation at  $\sim 1.55 \mu\text{m}$  wavelengths have been recently developed using LT- $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,<sup>7</sup> ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,<sup>8</sup> and ErAs: $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ <sup>9</sup> photoconductive materials. However, the main shortcoming of these photoconductive-based photomixers driven by two  $1.55 \mu\text{m}$  lasers is insufficient THz output power. In this letter, we study the properties of ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixers coupled to TEM-HA. When excited by two  $\sim 1.55 \mu\text{m}$  lasers, the photomixer devices deliver output power of  $0.1 \mu\text{W}$  at 700 GHz. The performance of the photomixer devices are investigated in both Ohmic transport and recombination limited transport regimes. Fundamental limitations on the operating characteristics of photomixer devices in the regime of recombination-limited transport are addressed.

The  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  materials used as photoconductive materials are grown by molecular beam epitaxy on top of a semi-insulating InP:Fe substrate and a 200 nm thick  $\text{In}_{0.52}\text{Al}_{0.47}\text{As}$  buffer. The layers were then bombarded by heavy ions (Br<sup>+</sup>) of high initial energy (11 MeV) at  $4 \times 10^{11} \text{ ion cm}^{-2}$ . An electron beam lithography/lift-off technique was used to pattern the  $2.5 \mu\text{m}$  photoconductive gap and  $50 \Omega$  coplanar waveguide (CPW) using Ti/Au (20/400 nm). The estimated photoconductor capacitance is  $C=1 \text{ fF}$ .

Furthermore, a thin cap layer of optically transparent silicon nitride was grown as an antireflection and surface passivation coating. The TEM-HA, with an impedance of  $R=65 \Omega$ , consists of a triangular conductive sheet (length=3 mm, base=2.6 mm) inclined above the ground state and supported by a small polytetrafluoroethylene (PTFE) block, as shown in the inset of Fig. 1.

The dc current-voltage (I-V) characteristic under illumination is represented in the inset of Fig. 3. Below 1.1 V, the I-V characteristic is linear indicating an Ohmic regime and above 1.1 V, the I-V characteristic becomes quadratic. The Ohmic behavior is expected for small bias voltages since the transit time between electrodes is longer than the average lifetime of carriers and the collection region between the electrodes is essentially space-charge neutral. However, a region of negative space charge begins to form at higher voltage when the time of the complete neutralization of electrons and holes injected at opposite electrodes becomes comparable with the average lifetime of carriers  $\tau_h - \tau_e$ , where  $\tau_e$  and  $\tau_h$  are the electron and hole lifetime, respectively. The quadratic I-V relation observed above 1.1 V is thus expected to be due to space-charge effects in the presence of recombination limited transport.<sup>10</sup>

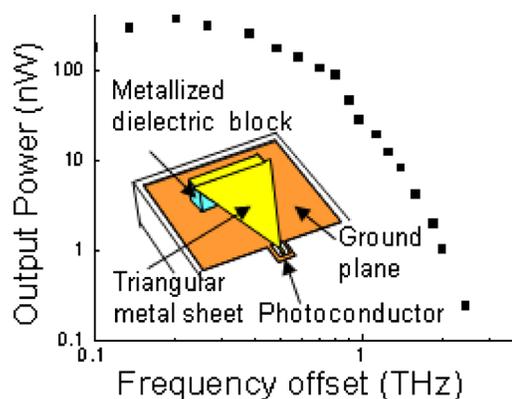


FIG. 1. (Color online) Output power of ion-irradiated- $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixers coupled to TEM HA vs the frequency difference between the two lasers. The bias voltage was 1.28 V and the total optical power incident was 100 mW. Inset: Schematic of the devices.

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The THz measurements use two laser diodes operating near 1550 nm, single-mode fiber-optic combiners and an erbium-doped amplifier to drive the photomixer devices. The THz beam is collected by an  $f/1$  off-axis parabolic mirror placed to collect the radiation with a maximum angle above the ground plane of approximately  $\alpha=45^\circ$ . Using a PTFE lens, the radiation is focused on a liquid-helium-cooled silicon bolometer with a responsivity given by the manufacturer of  $3.6 \times 10^5$  V/W.

Figure 1 shows the estimated power as a function of the frequency difference between the two lasers. The spectrum was acquired by pumping the photomixer with 100 mW total optical power and with a bias voltage of 1.28 V. The output power reached a maximum of  $0.38 \mu\text{W}$  at 200 GHz. At 700 GHz, the output power is  $0.1 \mu\text{W}$ , a value  $4\times$  higher than that delivered by previously reported ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixers coupled to standard spiral antennae.

The response of the photomixer coupled to the TEM-HA is relatively flat up until approximately 400 GHz. This response is essentially governed by two opposing effects: the narrowing of the radiation pattern which allows a better collection of the THz power offsets the loss of photoelectron response with frequency. Above 400 GHz, the detected power rolls off at a rate of approximately 6 dB/octave due to the limitation of the electron lifetime [ $f_{\tau_e}=1/(2\pi\tau_e)=265$  GHz]. At frequencies higher than 1 THz, the power drops abruptly at a rate of approximately 20 dB/octave. This roll-off is influenced by several contributions. In addition to the 6 dB/octave roll-off due to the electron lifetime, a main contribution of approximately 12 dB/octave is due to the coupling efficiency between the THz source and the even CPW electromagnetic mode.<sup>4</sup> The roll off induced by the  $RC$  constant starts at higher frequency since  $f_{RC}=1/(2\pi RC)=2.4$  THz.

Previous works have shown that the output powers of photomixer devices operating in the regime of recombination-limited transport do not increase quadratically with bias voltage as observed in a regime of Ohmic transport. Brown *et al.*<sup>11</sup> have demonstrated a quartic increase in output power with bias voltage at 200 MHz using photomixers made from LTG GaAs material. Saturation of the output power in this non-Ohmic regime was also observed at THz frequencies.<sup>12,13</sup> To provide further insight into the behavior of photomixers operating in a regime of recombination-limited transport, we have examined the output power delivered by photomixer devices as a function of the bias voltage and the incident optical power. Figure 2 shows the output power at a frequency of 688 GHz as a function of the dc photocurrent  $i_{dc}$  for several fixed bias voltages. The varied parameter is the optical power incident on the photomixer device. Note that each curve corresponds to very distinct excitation conditions. For bias voltages lower than  $V_c$ , all the curves are superimposed whatever the excitation conditions. This is in agreement with the expression of the radiated power given by photomixing theory  $P_{out}=\langle i_{ac}^2 \rangle R_L$ , where  $i_{ac}$  is the rms average of the ac current at the difference frequency and  $R_L$  is the impedance of the load circuit, if we consider that the ratio  $i_{ac}/i_{dc}$  is constant at a fixed difference frequency. However, for a bias voltage higher than  $V_c$ , smaller THz output power is observed. At voltage higher than  $V_c$ , the impedance of the photoconductor is lower than

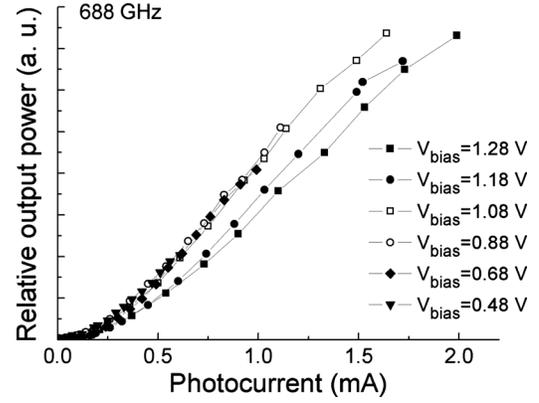


FIG. 2. Output power at 688 GHz as a function of the photocurrent at constant bias voltage of 0.48, 0.68, 0.88, 1.08, 1.18, and 1.28 V. The varied parameter is the optical power incident on the photomixer device.

the one in the Ohmic regime since the I–V characteristic is superlinear. An improved impedance matching of the photoconductor to the CPW and the TEM-HA is then expected in the regime of recombination-limited transport. This impedance matching change should result in an increase in the THz output power in the recombination-limited transport regime and then cannot explain the observed reduction in the THz output power at voltage higher than  $V_c$ . A second set of measurements was carried out to examine the output power as a function of bias voltage for several incident optical powers. As shown in Fig. 3, for all incident optical powers, as long as the bias voltage is lower than  $V_c$ , the output power is nearly proportional to the voltage squared, in agreement with the photomixing theory. However, the output power saturates at voltages higher than  $V_c$ . The dashed lines in Fig. 3 illustrate quadratic functions. This tendency was observed in the whole frequency range available using our experimental setup, from 60 GHz to 1.5 THz. These two sets of measurements clearly demonstrate the reduced performances of the photomixer devices at THz frequencies in the regime of recombination-limited transport.

To explain these limitations, transit time effects have to be considered in the description of the devices. Indeed, in the regime of recombination-limited transport, the photomixer no longer behaves as an ideal photoconductor; instead, it develops some of the characteristics of transit-time devices.<sup>14</sup> Therefore, if the optical beat frequency satisfies the condition  $\nu_2 - \nu_1 \ll \tau_{transit}^{-1}$ , a quartic dependence of the output power on

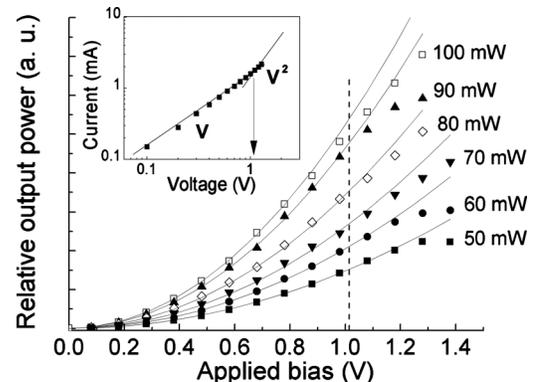


FIG. 3. Output power at 688 GHz vs voltage at fixed optical power of 50, 60, 70, 80, 90, and 100 mW. Inset: Current under illumination as a function of the bias voltage in ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixer.

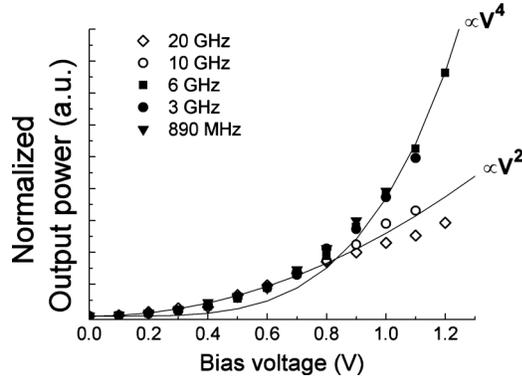


FIG. 4. Normalized output power as function of bias voltage at 890 MHz, 3 GHz, 6 GHz, 10 GHz, and 20 GHz. The curves were normalized by the output power values at 0.6 V for clarity of the figure. Dashed and dot lines show quadratic and quartic dependence of output power on bias voltage.

bias voltage should occur in a non-Ohmic regime since the photocurrent increases quadratically with the increase in bias voltage. Yet, if the difference frequency satisfies the condition  $\nu_2 - \nu_1 \gg \tau_{\text{transit}}^{-1}$ , the output power should saturate with the increase in the bias voltage because the bandwidth of the photomixer device is limited by the transit-time.<sup>14</sup> To investigate how injected space charge sets an upper limit on the performances of devices based on photoconductive phenomena, we have performed measurements in the frequency range from 1 to 50 GHz. For this purpose, photomixers directly connected to an electrical CPW structure were fabricated. The active  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layers were irradiated at  $1 \times 10^{12}$  ion  $\text{cm}^{-2}$ . Four  $0.2\text{-}\mu\text{m}$ -wide gold interdigitated electrodes with gap spacing of  $1.8 \mu\text{m}$  were placed on the top of the absorbing area. The characteristic impedance of the CPW was designed to be  $50 \Omega$  to facilitate the measurement of the photomixer output signal at microwave frequencies. In these ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  materials, the electron lifetime is reduced to  $0.33$  ps and the photoelectron mobility measured by optical pump-THz probe experiments<sup>15</sup> is  $3600 \text{ cm}^2/\text{V}\cdot\text{s}$ . From the crossover voltage from Ohmic to quadratic behavior  $V'_c = 0.8$  V observed in I-V characteristic, the ambipolar transit-time defined by  $L^2(\mu_e + \mu_h)/(\mu_e \mu_h V_c)$ , can be estimated. If we assume  $\mu_h = 450 \text{ cm}^2/\text{V}\cdot\text{s}$ , we find a transit time of  $\tau_{\text{transit}} = 105$  ps. At the crossover voltage from Ohmic to quadratic behavior,  $\tau_{\text{transit}}$  becomes comparable with the average lifetime of carriers  $\tau_h - \tau_e$  and we can then deduce a hole lifetime of  $\tau_h \sim 105$  ps in  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  material irradiated at dose of  $1 \times 10^{12}$  ion  $\text{cm}^{-2}$ . The output power delivered by the photomixers was measured using an electrical spectrum analyzer. Figure 4 shows the normalized output power of the photomixer as function of bias voltage at 890 MHz, 3 GHz, 6 GHz, 10 GHz, and 20 GHz. The output power at each frequency was normalized by its value at 0.6 V for the clarity of the figure. For all frequencies, as long as the bias voltage is lower than  $V'_c$ , the output power is proportional to the squared bias voltage. However, at voltages higher than  $V'_c$ , very distinctive tendencies are observed. At 20 GHz, the output power saturates as observed in the THz range, whereas at 10 GHz the output power increases nearly quadratically with an increase in bias voltage. At 6 GHz, 3 GHz, and 0.9 GHz, the dependence on bias voltage becomes superquadratic and

above 1 V, a quartic dependence of the output power on bias voltage is observed as expected from photomixing theory. These measurements demonstrate that for frequencies lower than 10 GHz, the photomixer device operates as an ideal photoconductive element in a regime of recombination limited transport, limited only by carrier lifetime and the RC constant. A transition occurs at approximately 10 GHz, and above this frequency, the photomixer shows reduced performance characteristics due to its operation as a transit-time limited device. The transit time corresponding to a transition frequency of 10 GHz is  $\tau_{\text{transit}} = 100$  ps, which is a value very close to that of the transit time  $\tau_{\text{transit}} = 105$  ps estimated from the crossover voltage between Ohmic behavior and the recombination limited transport. This agreement between the values of transit time estimated from the I-V characteristics and from frequency-resolved output power measurements strongly supports our analysis. The output power delivered by the photomixer device at frequency higher than 10 GHz is mainly due to photoelectrons due to their smaller carrier lifetime and larger drift velocity.

In conclusion, room temperature ion-irradiated  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  photomixers coupled to TEM HA has been demonstrated to deliver output power of up to  $0.1 \mu\text{W}$  at  $0.7$  THz using  $1.55 \mu\text{m}$  telecom-based technology. In the regime of recombination limited transport, the photomixer devices based on photoconductive material suffer a reduction in performance at THz frequencies due to transit time effects.

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