Side-illuminated fully ballistic p-i-n diode-based photomixer at 1550 nm

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***Abstract*—We report on a fully-ballistic (FB) p-i-n diode operating as a continuous-wave (CW) photomixing source at 1550 nm and optically fed from the side through a passive optical waveguide (POW) integrated within the diode heterostructure, demonstrating a dynamic range (DR) above 35 dB at 1 THz and obtaining photocurrents of at least four times the photocurrent of top illuminated diodes.**

I. INTRODUCTION

FOR terahertz (THz) applications that require large bandwidth and high frequency resolution, CW photomixing systems are an excellent choice with bandwidths greater than 2 THz and MHz resolution. Two slightly detuned lasers are beaten in a photomixer generating an AC current at the difference frequency which is then fed to an antenna. Telecom technology at 1550 nm provides cost-effective components and lasers. Here, p-i-n diodes are one of the preferred sources for CW photomixing systems, in combination with commercially available and inexpensive DFB lasers with linewidths on the MHz and sub-MHz range. In this work, we present a p-i-n diode design optimized for high frequency operation through ballistic transport and with an increased absorption efficiency by side illumination and evanescent coupling through a monolithically integrated passive optical waveguide (POW).

II. FULLY-BALLISTIC P-I-N DIODE

The high frequency operation of p-i-n diodes is affected by two factors: RC roll-off with a 3dB roll-off frequency of $f_{RC}^{3dB} = (2\pi RC)^{-1} \propto d_i$, where the capacitance $C = \epsilon_o \epsilon_r A/d_i$, with the permittivity of the intrinsic layer $\epsilon_0 \epsilon_r$, the area of the p-contact A, the thickness of the intrinsic layer d_i, and the antenna radiation resistance R. The other factor is transit-time roll-off, with a 3dB roll-off frequency that can be approximated for an average velocity $\bar{v}$ as $f_{tr}^{3dB} \approx (2\tau_{tr})^{-1} \propto d_i^{-1}$, where $\tau_{tr} = d_i/\bar{v}$. There exists a tradeoff between both roll-offs for the design of the diodes [1, 2]. For an antenna coupled device, the terahertz radiated power is

$$P_{THz} = \frac{1}{2} R I_{ph}^2 \left(\frac{1}{1+(f/f_{tr}^{3dB})^2}\right)\left(\frac{1}{1+(f/f_{RC}^{3dB})^2}\right), \quad (1)$$

where I_{ph} is the photocurrent. The fully-ballistic (FB) p-i-n diode presented here is optimized for high frequency operation through the following mechanisms: 1) in order to avoid noteworthy contribution of slow holes to the photocurrent, absorption takes place in a thin layer with non-zero field near the p-contact of the diode. This is achieved by grading the Al content within the In(Al)GaAs intrinsic layer, increasing the band-gap of the photoconductor beyond the 1550 nm photon energy. 2) The diode is designed to work ballistically over the whole transport length by making use of the velocity overshoot of electrons in InGaAs for energies well below the side-valley energy ($\Delta E_{\Gamma L}$). The intrinsic layer is designed such that electrons will not reach a kinetic energy of the order of $\Delta E_{\Gamma L}$ during transport under optimum biasing conditions. Therefore, inter-valley scattering, which would randomize the direction of motion of the electrons and degrade the average velocity [2], is largely suppressed. 3) The laser beam is fed from the side of the diode through a monolithic POW formed by InGaAsP and InP layers [3], drastically increasing absorption and hence the photocurrent at a given laser power.

III. WAVEGUIDE-COUPLED SIDE ILLUMINATION

For basically any efficient THz p-i-n diode concept, the optical absorber layer is comparatively thin, typically less than 100 nm. For top-illumination this results in an absorption less than 10%. The absorption efficiency of POW coupled diodes is strongly increased as propagation of the laser along the absorber layer allows theoretically close to 100% absorption. The monolithically integrated POW is shown in Fig. 1 and the insets in Fig. 2. The feeding waveguide is formed within the n^+ layers of the diode heterostructure, with the n^+-InP contact layer being the bottom cladding of the POW. Besides a thin guiding InP ridge that confines the width of the optical mode, the top cladding is air. A high refractive index n^+-InGaAsP (Q1.26) layer serves as the core of the waveguide. Once the optical mode reaches the area under the active mesa of the diode, the light will be coupled upwards into the high index In(Al)GaAs layers, where it is absorbed, generating the photocurrent. The diode can also be seen as a waveguide, with the In(Al)GaAs being the core, surrounded by the p^+- and n^+-InP lower refractive indices. In the absence of losses, the complete optical power is transferred between the two waveguides at each multiple of the coupling length [4] $L = \pi/(2k)$, where k is the coupling coefficient of the mode.

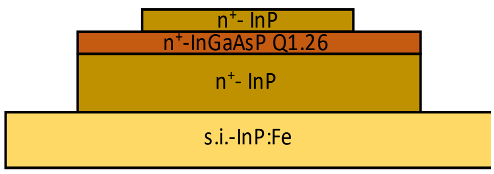

Fig. 1. Cross-section of the POW design from [5].

The coupling was studied numerically and optimized by Peng in [5], obtaining a coupling length of 5 µm with effective photon absorption efficiencies of 32 % for 8 µm long mesas and up to 50 % for 16 µm. Although larger mesas might reach arbitrary high efficiencies, practical devices must limit the length of the mesa (i.e. the absorber) in order to yield only few fF capacitances that are required for THz operation. This way, their high frequency performance is not drastically harmed through a decreasing RC-roll off frequency. Reflections at the waveguide facet also reduce the external efficiency when coupling from free space into the monolithic waveguide. The generated photocurrent obtained from an incident optical power P_{opt} and with an external efficiency η can be calculated as

$$I_{ph} = \eta e P_{opt}/(h\nu), \qquad (2)$$

where e is the elementary charge and $h\nu$ the photon energy.

IV. Results

A device with a 17 μm long mesa and $d_i = 200$ nm integrated with a bow-tie antenna has been characterized using a Toptica Photonics AG CW 1550 nm system. The optical signal is amplified by an erbium-doped fiber amplifier (EDFA) and coupled into the POW using a lensed single-mode fiber (SMF) with a spot diameter of 2.5 μm and a working distance of 14 µm.

The maximum measured photocurrent was 3.5 mA for an optical power of only 25 mW, corresponding to an absorption efficiency of 11 %, more than four times higher than by top-illumination, provided by a device with an optical window size of 5.5 × 4.5 µm^2 in a mesa with a total size of 8 × 10 µm^2, showing a maximum of 0.8 mA, corresponding to an efficiency of a 3 %. Both results were taken for a bias of -0.2 V. The reflections of the optical signal when coupling from the SMF to the POW are not considered in this calculation. If a planar incidence on the InP facet is considered, a 27 % of the power is reflected (-1.37 dB loss). Thus the external quantum efficiency for coupling from the POW to the fully ballistic p-i-n diode is 15 %, up to five time higher than the top-illuminated diode.

A recorded spectrum is shown in Fig. 2 with photocurrent of 11$\pm$1 mA and a bias modulation between -3 V and -0.6 V, using a total optical power of 250 mW, but this time with the SMF placed out of focus, reducing the power that couples into the POW by approximately a 50 % in order to avoid strong photocurrent drops during the measurement by drifts. The receiver was a commercial photoconductor from Toptica Photonics AG/HHI operating with 22 mW optical power. A dynamic range of 35 dB at 1 THz has been achieved for an integration time of 300 ms. The terahertz current provided by the receiver for different source photocurrents indicated a saturation around $I_{ph} = 10$ mA, as shown in Fig. 3. The saturation is more severe at lower biases, indicating current blockage and screening of the built-in field. A higher DC reverse bias can, to a certain degree, restore the optimal field for ballistic transport.

V. Conclusion

A fully-ballistic, passive optical waveguide-coupled (POW) p-i-n diode, achieving 35 dB of dynamic range at 1 THz in conjunction with a homodyne photoconductive receiver has been demonstrated. The POW improved the optical coupling efficiency by more than four times as compared to a top-illuminated device that use the same material.

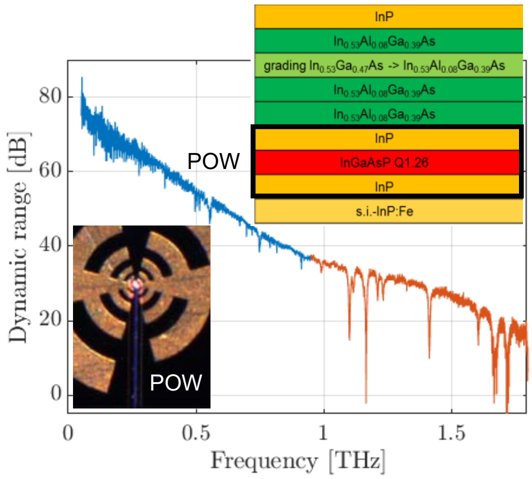

Fig. 2. Spectrum measured with a Toptica CW 1550 nm system. The dynamic range corresponds to an integration time of 300 ms. The two colors indicate two different laser configurations in order to reach a higher measurable range. Insets: material heterostructure with the POW layers indicated and a photograph of a waveguide-coupled device attached to a log-periodic antenna. The data shown here are taken with a bow-tie antenna.

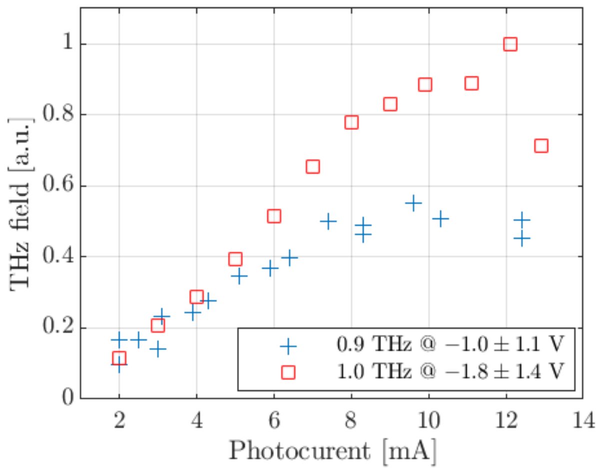

Fig. 3. Measured terahertz field (in arbitrary units) at 0.9 and 1 THz for two different bias settings. In both cases, a saturation at approximately 10 mA is observed. Above 12 mA the photocurrent was unstable.

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