InP Double Heterojunction Bipolar Transistor for broadband terahertz detection and imaging systems

D Coquillat¹,², V Nodjiadjm², A Konczykowska², N Dyakonova¹, C Consejo¹, S Ruffenach¹, F Tappe¹, M Riet², A Muraviev³, A Gutin³, M Shur³, J Godin², W Knap¹

¹ Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS-Université de Montpellier, Montpellier, France
² III-V Lab (Bell Labs, TRT and CEA/LETI joint Lab), Route de Nozay, 91460 Marcoussis, France
³ Rensselaer Polytechnic Institute, Troy, New York 12180, USA
E-mail: Dominique.Coquillat@univ-montp.fr

Abstract. This paper presents terahertz detectors based on high performance 0.7-µm InP double heterojunction bipolar transistor (DHBT) technology and reports on the analysis of their voltage responsivity over a wide frequency range of the incoming terahertz radiation. The detectors operated without any spatial antennas to couple terahertz radiation to the device and have been characterized in the 0.25 – 3.1 THz range with the responsivities (normalized to 1 W radiant power) of 5 V/W and 200 µV/W measured at 0.35 THz and 3.11 THz, respectively. The InP DHBTs also performed as the imaging single-pixels at room temperature in the raster scanned transmission mode. A set of the sub-terahertz images of plant leaves suggest potential utility of InP DHBT detectors for terahertz imaging dedicated to non-invasive testing of plants.

1. Introduction
Terahertz (THz) imaging has a large potential in the field of contact-free testing, for example in the field of non-destructive diagnosis of plants [1] and non-destructive testing of VLSI. Such applications require compact devices that operate at room temperature over a wide frequency range (0.1 to 10 THz). The recent developments of coded-aperture imaging with the single pixel detectors have led to new approaches for low cost real-time THz imaging [3,4]. This technique uses the dynamic spatial light modulators to multiplex and acquire the high-frame-rate images and requires the fast single-pixel detectors.

The existing THz single-pixel detectors that work at room temperature are bulky, slow, and prohibitively expensive. The development of low cost real-time THz imaging requires sensitive, fast, and robust room temperature detectors with a high dynamic range. Recently, InP DHBTs have attracted interest as sub-THz detectors [5,6] and compared favourably with the existing detectors based on the Schottky diodes [7], field effect transistors [8], or Si heterojunction bipolar transistors [9]. In this work, we evaluate InP DHBTs designed for 100 Gbit/s applications as single-pixel elements for the THz detection in the wide frequency range of 0.25 - 3.11 THz at room temperature. We also present two-dimensional images obtained at 0.67 THz in the raster scanned transmission mode and show that the resulting absorption directly reflects the quantity of water content in plant leaves.

To whom any correspondence should be addressed.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
2. Technology and experimental set up
To address high bit-rate optical communications applications, in particular 100 Gbit/s transmission, development of a submicron process was undertaken. To achieve such high bit-rate, the transistor should have $f_t/f_{\text{max}}$ in the 250-300 GHz range. The development of such a submicron InP DHBT technology was presented in Ref. 10, where in-depth study of device geometry and structure has allowed to get the needed performances and yield. The InP DHBTs used in this work have a 0.7-µm wide emitter contact. They demonstrated cut-off frequency and the maximum frequency of operation, $f_t$ and $f_{\text{max}}$, above 320 and 280 GHz, respectively [10,11]. The static current gain is around 40 and the common-emitter breakdown voltage is above 5V. In this work, they operate as the THz detectors without any spatial antenna to couple the THz radiation to the device. The metallization of the contact pads and bonding wires act as effective antennas. For sub-THz photoresponse measurements, the DHBTs were exposed to the focused beam from one of the two tunable electronic sources covering the ranges from 0.26 to 0.37 THz and from 0.64 to 0.69 THz with output power ~ 1 mW (Fig. 1a). For frequencies above 1 THz, the photoresponse $\Delta u$ was measured with a continuous-wave CO$_2$–pumped molecular gas laser emitting at 1.40, 2.52, and 3.11 THz with the maximum output powers of ~ 100 mW, 150 mW, and 90 mW, respectively. The radiation was focused on the transistor surface using parabolic mirrors and the radiation intensity was modulated by a chopper. The emitter terminal of the device was grounded and the base-emitter bias $V_{BE}$ was controlled by a Keithley Source Meter. The base-emitter bias and radiation frequency dependence was measured using a lock-in amplifier. For THz imaging, parabolic mirrors were used to focus the beam to the focal point, and the object (a fresh or dry plant leaf) was mechanically scanned using computer controlled translation stages.

3. Experimental results and discussion
In Fig. 1b, we have plotted the induced $dc$ collector-emitter voltage $\Delta u$ (photoresponse) of the 0.7-µm DHBT as a function of base-emitter bias $V_{BE}$ applied in order to increase the sensibility of the THz detector. In this case, zero collector-emitter bias was applied, $V_{CE} = 0$. The optimal THz detection bias conditions were achieved when $V_{BE}$ was close to 0.6 V. Above this value, the photoresponse was a decreasing function of $V_{BE}$.

![Figure 1. a) InP DHBT operating in detector mode for induced $ac$ photovoltage. b) Photoresponse for 2.52 THz radiation as a function of the base-emitter bias $V_{BE}$. Inset: The polarization of the electric field of the incident THz radiation is parallel to the base-to-collector direction.](image_url)

The value of the optimal photoresponse at 2.52 THz was ~ 200 µV for the beam focused by a f/1 off-axis parabolic mirror. For a power at the focal plane of approximately 150 mW, the responsivity, $R_{1W}$, normalized to 1 W radiant power was ~1.33 mV/W. It should be noted that the corresponding area-normalized responsivity calculated with regard to the area of the device taken equal to diffraction limited
area [12] is 15.9 times larger than this value. The log-log plot of the responsivity measurements is depicted in Fig. 2. The device responsivity rolls off non-linearly with increasing frequency and follows a $\omega^{-4}$ law as shown by the guide for the eye included as a dashed dotted line. This dependence can be explained by the combined effects of the capacitance, $C$, shunting the active nonlinear device resistance, $R$, and parasitic series inductance, $L$. At high frequencies the voltage drop $V_R$ across $R$ becomes independent of $R$ and proportional to $1/(\omega^2 LC)$. The detector response is proportional to $V_R^2$, and, therefore inversely proportional to $1/(\omega^4 L^2 C^2)$.

**Figure 2.** Log-log plot of responsivity (normalized to 1 W radiant power) as a function of frequency of the incident radiation (for $V_{BE} \sim 0.7$ V). The black dashed dotted line is a guide for the eye.

Using the same InP DHBT, we have performed raster scan imaging in transmission mode as shown in Fig. 3. The objects to image (Fig. 3a) are a fresh and a dry leaves of a viburnum tinus plant (71 mm × 80 mm). By focussing the source beam with a parabolic mirror, we achieved an almost Gaussian profile exhibiting full width at half maximum of 1.2 mm at 0.67 THz. The THz image (Fig 3b and 3c) is a result of the volume of water at the measured spot. It illustrates that small changes in water content of a leaf can be detected very sensitively using the InP DHBT detectors. Fig. 3d shows the measured transmission in the 0.64 – 0.69 THz range through a fresh leaf and a dry leaf of a viburnum tinus plant.

**Figure 3.** a) Visible image of a fresh leaf (bottom) and a dry leaf (top) of viburnum tinus. b) The transmitted 0.67 THz intensity measured using an unbiased InP DHBT detector reveals the detailed structure of the leaves in linear scale and c) in logarithmic scale. Applying a logarithm operator to the image can be useful when the dynamic range is too large to be displayed. d) Transmission of the leaves as a function the frequency in the 0.64 – 0.69 THz frequency range.
Conclusion
In conclusion, we demonstrated the detection in wide frequency range of 0.25 - 3.1 THz electromagnetic radiation by InP DHBTs at room temperature. They can operate far above the frequencies at which they have gain and can still rectify THz current and voltage. These cost-efficient detectors can be used in a wide frequency range to monitor the water content of leaves and plants.

Acknowledgments
This work was partly supported by the ANR P2N NADIA “Integrated NAno-Detectors for terahertz Applications” (ANR-13-NANO-0008), by the “Contrat de Plan Etat Région du Languedoc Roussillon 2015-2020: BioNanoImaging Foundry”, and by the Region of Languedoc-Roussillon through the “Terahertz Platform”. The work at RPI is supported by Army Research Laboratory (ARL) Multiscale Multidisciplinary Modeling of Electronic Materials (MSME) Collaborative Research Alliance (CRA) (Grant No. W911NF-12-2-0023, Program Manager: Dr. Meredith L. Reed).

References
[1] Born N, Behringer D, Liepelt S, Beyer S, Schwerdtfeger M, Ziegenhagen B and Koch M 2014 Plant Physiol. 164 1571
[2] Stillman W, Veksler D, Elkhatib T A, Salama K, Guarin F and Shur M S 2008 Electronics Letter 44 22
[3] Chan W L, et al. 2009 Appl. Phys. Lett. 94 213511
[4] Watts C M, et al. 2014 Nature Photonics 8 605
[5] Coquillat D, Nodjiadjim V, Konczykowska A, Riet M, Dyakonova N, Consejo C, Teppe F, Godin J, Knap W 2014 Proc. 39th IRMMW-THz: Int. Conf. on Infrared, Millimeter, and Terahertz Waves (Tucson, AZ, USA)
[6] Suszek J, Siemion A, Coquillat D, Nodjiadjim V, Konczykowska A, Riet M, Sobczyk A, Zagrajek P, Palka N, Czerwińska E, Blocki N, Kolodziejczyk A, Dyakonova N, Teppe F, Consejo C, Knap W, Sypek M 2015 Proc. 40th IRMMW-THz: Int. Conf. on Infrared, Millimeter, and Terahertz Waves (Hong Kong, China)
[7] Han R, Zhang Y, Coquillat D, Videlier H, Knap W, Brown E, Kenneth K O 2011 IEEE J. of Solid-State Circuits 46 2602
[8] Knap W, Nadar S, Videlier H, Boubanga-Tombet S, Coquillat D, Dyakonova N, Teppe F, Karpiacz K, Lusakowski J, Sakowicz M et al. 2011 J. of Infrared Millimeter and Terahertz Waves 32 618
[9] Al Hadi R, Grzyb J, Heinemann B, Pfeiffer U 2012, Proc. IEEE Bipolar/BiCMOS Circuits and Tech. Meeting
[10] Godin J, Nodjiadjim V, Riet M, Berdagué P, Drisse O, Derouin E, Konczykowska A, Moulu J, Dupuy JY, Jorge F, Gentner JL, Scavenneac A, Johansen T, Krozer V 2008 Proc. Compound Semiconductor Integrated Circuits Symposium, CSIC’08, IEEE 1 (Monterey, CA, USA)
[11] Dupuy JY, et al. 2013 IEEE Transactions on Microwave Theory and Techniques 61 517.
[12] Tauek R, Teppe F, Boubanga S, Coquillat D, Knap W, Meziani Y, Gallon C, Boeuf F, Skotnicki T, Fenouillet-Beranger C, Maude D K, Rumyantsev S, and Shur M S 2006 Applied Physics Letters 89 253511