High Dynamic Range THz Systems using ErAs:In(Al)GaAs Photoconductors

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***Abstract* — This paper reviews progress on ErAs:In(Al)GaAs photomixers for operation with telecom lasers at 1550 nm, including linearity and absorption coefficient measurements, specifications, packaging example, and applications in vector spectrometry. We have achieved a receiver noise equivalent power as low as 1.81 fW/Hz at 188 GHz under continuous-wave operation and a bandwidth of more than 6 THz and a peak dynamic range of 89 dB under pulsed operation.**

***Keywords* — terahertz, photoconductor, telecom wavelength, continuous-wave, time domain spectroscopy, vector spectroscopy.**

I. Introduction

Within the past two decades, room-temperature operated Terahertz (THz, 100 GHz-10 THz) sources and receivers have advanced rapidly, including electronic [1], optical [2] and photonic devices. Photonic systems consist of photoactive semiconductor devices that are driven by a laser signal. The laser signal consists either of a single, 100 fs-scale pulse with a bandwidth of several THz or of two heterodyned continuous-wave (CW) laser beams with a frequency difference in the THz range. The semiconductor device absorbs the laser signal, effectively resulting in mixing the frequency components of the optical signal and consequently generating an AC current at these frequencies. In most cases, the current is fed into an antenna to emit THz radiation. Electrical systems yet offer the largest dynamic range in the range of 120 dB around 300 GHz [1], however, at cost of bandwidth which is usually 50% of the center frequency at best. Photonic systems have caught up in the past years, yet offering a peak dynamic range around 105 dB [3] while they cover at the same time a bandwidth of several THz with a single system. For this reason, many spectroscopic applications have been performed with photonic systems. A further field of applications is communication where the photonic device down-converts a data stream encoded on a 1550 nm signal to a mm-wave wireless signal [4] or to an electrical signal for a data processing unit. Industrial applications are in the field of non-destructive testing, e.g. [5].

Photoconductors, play an essential role in almost all photonic Terahertz systems. Photoconductors are optically switched resistors with sub-ps recovery time. Upon optical excitation, they become conductive due to generation of electron-hole pairs via absorption. In order to respond to a THz-modulated signal, the carriers are trapped on a sub-ps time scale by specially designed defects therefore removing the carriers from transport and restoring the initial high resistance.

In pulsed systems, photoconductors serve as both sources and receivers. Below 4 THz, well designed photoconductors outperform nonlinear crystals that can be alternatively used. In CW systems, they are frequently employed as homodyne receivers.

Of particular importance nowadays is compatibility with 1550 nm driving lasers in order to make use of telecom lasers and components for the optical part of the system which is a major cost factor. This imposes certain requirements on the photoconductive material. First, it must be capable to absorb the 1550 nm laser signal. Most efficient are interband transitions that require a band gap energy below 0.8 eV. InGaAs has proven to be a viable material for this purpose. Unfortunately, the low band gap, E_G, reduces the maximum bias field, E_{bd}, that can be applied to the device which empirically scales as $E_{bd} \sim E_G^{2.5}$ [6] and increases undesired dark currents. These limitations reduce the emitted THz power of photoconductive sources as the THz-modulated resistance must be DC biased in order to generate a THz current. Further requirements are a large carrier mobility in order to maximize the generated current at a given DC bias and, in the case of CW devices and receivers in general, a short carrier lifetime which allows the material to recover to the high resistance after optical excitation.

This paper summarizes recent results of telecom-wavelength compatible ErAs:In(Al)GaAs photoconductors with outstanding performance parameters.

II. The Material System

ErAs:(InAl)GaAs photoconductors consist of a superlattice structure of semi-metallic ErAs clusters that act as efficient carrier trapping centers and an InGaAs absorber. For sources, InAlAs layers are further included. Typical band structures for sources and receivers are illustrated in Fig. 1 a) and b) respectively. The devices typically consist of 70-100 superlattice periods of the illustrated structures. Further details can be found in [7] and [8]. For both sources and receivers, the absorption takes place in the InGaAs layers. Carriers then drift to the ErAs clusters where they are trapped. For sources, they need to tunnel through adjacent p-doped InAlAs layers with a thickness in the range of 2 nm. These layers assist to improve the device resistance.

Fig. 2 shows the absorption profile of a receiver structure with a thickness of the active layer of 1 µm. The absorption coefficient is around 5500-7100/cm for the telecom wavelength range (1525-1600 nm). The carrier lifetime of the receivers is in the range of 510fs [9], while Al-containing devices feature lifetimes above 1 ps typically.

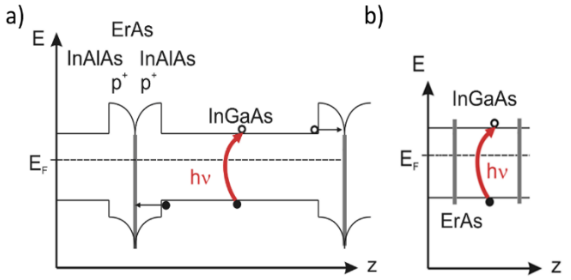

Fig. 1. a) Typical band structure of an ErAs:In(Al)GaAs source and (b) an ErAs:InGaAs receiver.

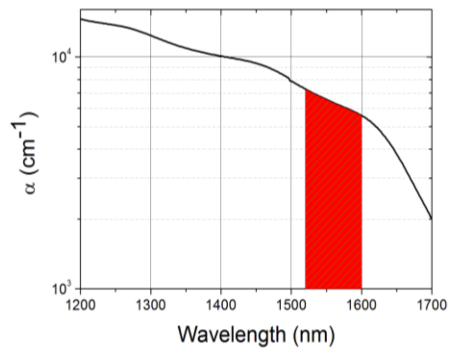

Fig. 2. Spectrally resolved absorption coefficient of an ErAs:InGaAs receiver

III. Results

Inset of Fig. 3 illustrates a packaging example of an ErAs:In(Al)GaAs photoconductor that is frequently used in experiments. Under CW operation, the receivers feature a measured noise equivalent power (NEP) as low as 1.81 fW/Hz at 188 GHz [10] which increases to about 100 fW/Hz at 1 THz. These data are as recorded and not idealized values. The intrinsic, theoretical NEP limit at 200 GHz is estimated to be in the low aW/Hz range, given perfect THz coupling and negligible external noise contributions [10]. The devices feature a large linearity range. At the maximum available power of a CW system of 150 µW at 200 GHz we did not see any saturation. We did see some saturation for THz powers beyond the several mW level using a backward wave oscillator at 100 GHz, however, the devices tend to take damage at these high power levels. With an ErAs:In(Al)GaAs source, we achieved a dynamic range of 78 dB at an integration time of 300 ms with a laser power of only 26 mW in each photoconductor, i.e. source and receiver [7]. The extrapolated bandwidth is about 3.6 THz. Combined with powerful p-i-n diode-based photomixer sources, peak dynamic ranges beyond 100 dB should be feasible.

Under pulsed operation, ErAs:In(Al)GaAs devices are both excellent sources and receivers. Fig. 3 depicts a measurement with almost 90 dB peak dynamic range and a bandwidth beyond 6.2 THz. The source was composed of 90 periods of 15 nm InGaAs, 1.5 nm InAlAs, 0.8 ML p-delta-doped ErAs, and 1.5 nm InAlAs (Fig. 1a), attached to a 25 µm slotline antenna. The receiver consisted of 100 periods of 10 nm InGaAs, and 0.8 ML p-delta-doped ErAs (Fig.1 b) equipped with a 25 µm H-dipole antenna with a gap of 5 µm. The measurement was taken at a source bias of 150 V, a source laser power of 45 mW and a receiver laser power of 16 mW generated by a fiber-coupled Menlo C-fiber system. At this laser power, the source can be operated with 200 V bias without taking damage, i.e. the presented spectrum is obtained under safe operation conditions.

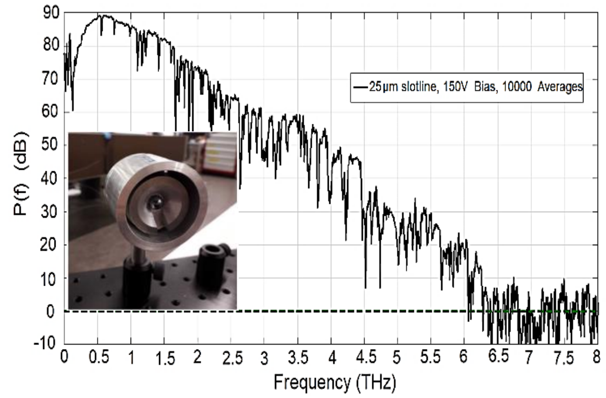

Fig. 3. Spectrum obtained with only ErAs:In(Al)GaAs photoconductors with fiber-coupled 1550 nm pulses as described in the text. The measurement time was approximately 17 minutes. Inset: APC connectorized packaging example including a 1 cm diameter silicon lens.

IV. Application Example: 1.5 Port Vector Spectrometer

This section summarizes recent results of a pulsed 1.5 port Terahertz time domain (TDS) vector spectrometer as discussed in ref. [11], using only ErAs:In(Al)GaAs photoconductors. The setup is illustrated in Fig. 4. The system uses three laser signals that originate from the same oscillator. One signal drives an ErAs:In(Al)GaAs source (Tx), the other two laser signals are guided through a delay stage each and drive two receivers (Rx1, Rx2). Rx1 measures the transmitted THz signal through a sample under test, whereas Rx2 measures the reflected signal. The wire grid polarizers (WGP) are implemented as beam splitters. WGP1 is aligned to 45° (~3 dB loss) with respect to the source polarization while WGP2 is vertical. This way, the reflected signal from the sample is again reflected by WGP1 towards Rx2 with an additional 3 dB loss. The setup is optimized for measuring the refractive index, the absorption coefficient and the thickness of a plane sample by a THz TDS. There is no mechanical measurement of the sample thickness necessary. Fig. 5 illustrates the measurement principle at the example of a high resistivity silicon wafer with a nominal thickness of 500 µm (manufacturer specification).

The transmission trace (under ambient air) shows a time delay between the pulse recorded with the empty setup (red) and the sample introduced in the setup (blue). The temporal distance between the two main peaks is $\Delta t_1=(n-1)d/c_0$, where c_0 is the vacuum speed of light, n is the refractive index of the material under test and d is the mechanical thickness. For simplicity, we assume the refractive index of air to be 1. The distance between the main peak and the first echo in both the transmitted and reflected signal is $\Delta t_2 = 2nd/c_0$. Usually the reflection measurement is better suited for lossy samples than the transmission measurement as the echo in the transmission measurement is often hardly visible. Therefore, the data quality is better for a synchronous measurement of R and T, resulting in reduced errors and larger bandwidth [11]. The equation system for Δt_1 and Δt_2 allows to solve for n and d individually. The absorption coefficient can be extracted from the transmission measurement amplitude. As the refractive index and the absorption coefficient may be frequency-dependent, the equation system is numerically evaluated by an algorithm for the frequency range under investigation [11]. For the silicon wafer, we determine a thickness of 498 ± 10 µm with a higher accuracy than a caliper measurement and in excellent agreement with the thickness of 500 µm according to the manufacturer specification. The refractive index is frequency-independent with a value of 3.25 ± 0.01 which is about 5% smaller than the literature value of 3.416. The absorption for the high resistivity silicon wafer is below the resolution limit. Though the presented characterization of a silicon wafer is a simple example, the setup and the algorithm is capable of characterizing more complex structures, including non-reciprocal devices such as isolators [12].

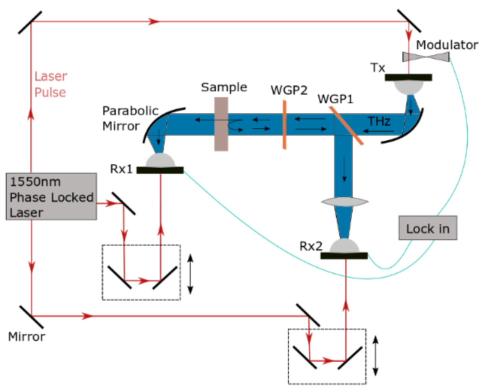

Fig. 4. Schematic of the 1.5 port vector spectrometer setup. Red lines: 1550 nm laser signals, blue: THz path.

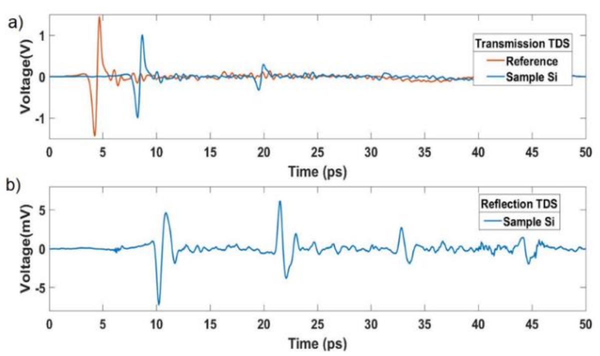

Fig. 5. Time domain traces for the transmission (a) and reflection (b).

V. Conclusion

ErAs:In(Al)GaAs photoconductors are versatile, powerful devices for both TDS and photonic CW systems at a competitive level with the best devices reported so far [3,13]. We have shown a first application of these devices in a 1.5 port vector spectrometer that measures the reflection and transmission synchronously. This improves the data quality and extends frequency coverage as compared to a standard TDS measurement.

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References

[1] http://www.vadiodes.com/en/wr3-4vnax, accessed April 23rd 2019

[2] S.I. Hayashi, K. Nawata, T. Taira, J.I. Shikata, K. Kawase, and H. Minamide, "Ultrabright continuously tunable terahertz-wave generation at room temperature," *Scientific reports* 4, p. 5045, 2014.

[3] T. Göbel, D. Stanze, B. Globisch, R. J. B. Dietz, H. Roehle, and M. Schell, "Telecom technology based continuous wave terahertz photomixing system with 105 decibel signal-to-noise ratio and 3.5 terahertz bandwidth," *Optics Lett.*, vol. 38, pp. 4197-4120, Oct. 2013

[4] M. Freire Hermelo, P.-T. Shih, M. Steeg, A. Ng'oma, and A. Stöhr, "Spectral efficient 64-QAM-OFDM terahertz communication link," *Opt. Express*, vol. 25, pp. 19360-19370, 2017.

[5] M. Stecher, C. Jördens, N. Krumbholz, C. Jansen, M. Scheller, R. Wilk, O. Peters, B. Scherger, B. Ewers, and M. Koch, "Towards Industrial Inspection with THz Systems" in *Ultrashort pulse laser technology* Springer International Publishing, pp. 311–335, 2016.

[6] J. L. Hudgins, G. S. Simin, E. Santi, and M. A. Khan, "An assessment of wide bandgap semiconductors for power devices," *IEEE Trans. Power Electron.*, vol. 18, pp. 907–914, 2003.

[7] A.d.J. Fernandez Olvera, H. Lu, A. Gossard, and S. Preu, "Continuous-wave 1550 nm operated terahertz system using ErAs:In(Al)GaAs photo-conductors with 52 dB dynamic range at 1 THz," *Opt. Express*, vol. 25, pp. 29492–29500, 2017.

[8] U. Nandi, et al. "1550-nm Driven ErAs: In (Al) GaAs Photoconductor-Based Terahertz Time Domain System with 6.5 THz Bandwidth." Journal of Infrared, Millimeter, and Terahertz Waves, vol. 39, pp. 340-348, 2018.

[9] J. Suen, P. Krogen, S. Preu, H. Lu, A. Gossard, D. Driscoll, and P. Lubin, "Measurement and modeling of ErAs:In0.53Ga0.47As nanocomposite photoconductivity for THz generation at 1.55 µm pump wavelength," *J.of Appl. Phys*., vol. 116, p. 013703, 2014.

[10] A.d.J. Fernandez Olvera, A. Roggenbuck, K. Dutzi, N. Vieweg, H. Lu, A. C. Gossard and S. Preu, "International System of Units (SI) Noise-Equivalent Power and Responsivity Characterization of Continuous Wave ErAs:InGaAs Photoconductive Terahertz Detectors," *Photonics*, vol. 6, pp. 15 (2019).

[11] F. R. Faridi, U. Nandi, and S. Preu, "1.5 Port Vector Spectrometer for Terahertz Time Domain Spectroscopy," in *2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, pp. 1–2, 2018.

[12] F.R. Faridi and S. Preu, "Characterization of a Terahertz Isolator using a 1.5 port Vector Spectrometer" submitted to the *44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, 2019.

[13] M. Yahyapour, A. Jahn, K. Dutzi, T. Puppe, P. Leisching, B. Schmauss, N. Vieweg, and A. Deninger, "Fastest Thickness Measurements with a Terahertz Time-Domain System Based on Electronically Controlled Optical Sampling," *Appl. Sciences, vol.* 9, 1283, 2019

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