GaN Terahertz Photodetectors for the Reststrahlen Gap of Intersubband Optoelectronics

Conference Paper · January 2017

DOI: 10.1364/CLEO_SI.2017.SM4J.7

5 authors, including:

Habibe Durmaz
Karamanoglu Mehmetbey Üniversitesi

Denis Nothern
Boston University

Theodore D Moustakas
Boston University

GaN Terahertz Photodetectors for the Reststrahlen Gap of Intersubband Optoelectronics

Habibe Durmaz[1,2,*], Denis Nothern[1], Gordie Brummer[1], Theodore D. Moustakas[1], and Roberto Paiella[1]

[1]*Department of Electrical and Computer Engineering and Photonics Center, Boston University, 8 St. Mary's St., Boston, MA 02215*
[2]*Department of Electrical and Electronics Engineering, Recep Tayyip Erdogan University, Zihni Derin Yerleskesi, Rize, Turkey 53100*
**Corresponding author: hdurmaz@bu.edu*

Abstract: Terahertz intersubband photodetectors are developed based on GaN/AlGaN quantum wells grown on a semi-polar GaN substrate, covering the frequency range that is fundamentally inaccessible to existing III-V semiconductor devices due to Reststrahlen absorption.

OCIS codes: (040.2235) Far infrared or terahertz; (230.5590) Quantum-well, -wire and -dot devices; (040.5160) Photodetectors

1. Introduction

Terahertz optoelectronic devices are technologically significant for a wide range of applications in biomedical sensing, security screening, spectroscopic imaging, and industrial process control. In the past several years, substantial progress has been reported in the development of THz active devices based on intersubband (ISB) transitions in GaAs/AlGaAs quantum wells (QWs), including quantum-well infrared photodetectors (QWIPs) and quantum cascade (QC) lasers [1]. The operation of these devices, however, is fundamentally limited to incomplete coverage of the THz spectrum, due to the prohibitively strong lattice absorption in the spectral vicinity of the (Al)(Ga)As optical phonons. The resulting forbidden Reststrahlen band around 8-9 THz represents a prominent gap in the spectral coverage of semiconductor optoelectronics [2].

Recently, III-nitride semiconductors have emerged as a promising materials platform to overcome this limitation [3-6]. By virtue of the large optical phonon frequencies of GaN/AlGaN QWs (above 15 THz), ISB devices based on these materials can operate at THz frequencies that are completely inaccessible to their arsenide-based counterparts due to Reststrahlen absorption. In addition, it has been argued based on Monte Carlo simulations that GaN THz QC lasers could potentially reach room-temperature operation [3], unlike existing devices which are intrinsically limited to cryogenic temperatures due to thermally activated LO-phonon emission. Initial experimental progress includes the report of THz ISB absorption [4], photodetection [6], and evidence of electroluminescence [5] in GaN/AlGaN QWs.

A key challenge in the development of III-nitride ISB devices is provided by the large internal electric fields that exist in GaN/AlGaN QWs grown along the polar crystallographic *c*-axis (the most common growth direction for these materials), due to spontaneous and piezoelectric polarizations. These internal electric fields create a triangular QW band lineup that tends to blue-shift the ISB transition energies, thus significantly complicating the design of long-wavelength ISB devices. In addition, due to their distorted lineups, these QWs cannot be used for the implementation of QWIPs based on the high-performance bound-to-quasi-bound design, where the upper subband is energetically lined up with the top of the barriers to facilitate carrier extraction [7]. To address these issues, here we develop THz ISB photodetectors based on GaN/AlGaN QWs grown on a free-standing semi-polar $(20\bar{2}\bar{1})$ GaN substrate [8], where the undesirable internal electric fields are strongly reduced. Promising devices are demonstrated, with responsivity spectra covering the entire Reststrahlen band of arsenide semiconductors.

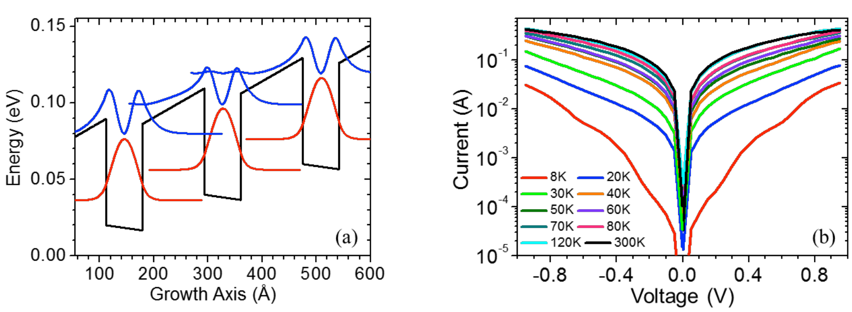

Fig. 1. (a) Conduction-band lineup and squared envelope functions of the bound states of the THz QWIPs developed in this work. (b) Temperature-dependent dark current-voltage characteristics.

2. Results and discussion

The QWIP active material consists of 30 GaN/$Al_{0.06}Ga_{0.94}N$ QWs, whose conduction-band diagram under bias is shown in Fig. 1(a). A relatively rectangular potential energy profile is computed for this structure, due to the small spontaneous and piezoelectric polarization fields of such semi-polar QWs. Each QW supports two bound-state subbands separated by 43 meV in energy, corresponding to an ISB transition frequency of approximately 10 THz. By design, the first-excited subband is close to the top of the barriers, so as to optimize the tradeoff between strong ISB absorption and efficient escape of the photoexcited carriers out of the wells [7]. This active material was grown by molecular beam epitaxy and then processed in mesa-structure devices. The top metal contact was patterned in the shape of a grating (with 15-μm period), in order to couple normally incident light to the QWs in a way consistent with the polarization selection rules of ISB transitions.

Figure 1(b) shows the dark current-voltage characteristics measured with one of these devices for different heat-sink temperatures. A significant decrease in dark current with decreasing temperature is observed, indicating a large contribution from thermionic emission out of QWs as expected based on standard models of carrier transport in QWIPs [7]. The symmetric shapes of these traces with respect to bias polarity are also consistent with the nearly rectangular shape of the QWs and the absence of substantial band bending due to internal electric fields.

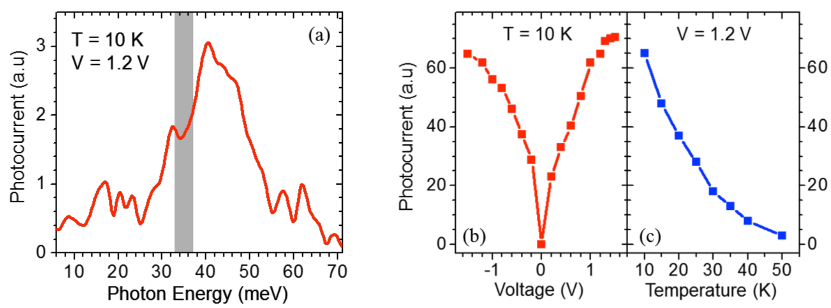

Fig. 2. (a) Photocurrent spectrum of a GaN/AlGaN QWIP developed in this work. The grey area indicates the Reststrahlen band of GaAs. (b) Photocurrent signal at a fixed temperature of 10 K measured as a function of applied voltage (c) Photocurrent signal at a fixed voltage of 1.2 V as a function of heat-sink temperature.

As shown in Fig. 2(a), pronounced photocurrent spectra are measured with these devices, peaked at a photon energy of about 42 meV, which is in excellent agreement with the calculated 43-meV ISB transition energy of Fig. 1(a). The bias-voltage and temperature dependence of the total photocurrent signal are illustrated in Figs. 2(b) and 2(c). The maximum temperature at which this signal can be resolved and the peak low-temperature responsivity inferred from these data are about 50 K and 10 mA/W, respectively, both of which are reasonable for THz-range QWIPs [7]. Importantly, the spectrum of Fig. 2(a) fully overlaps the Reststrahlen band of GaAs (~33-37 meV, as indicated by the grey area in the same figure). These data therefore clearly illustrate the ability of GaN/AlGaN QWs to cover this frequency range that has so far remained inaccessible to ISB optoelectronics. With further optimization of the growth process and QW design, the same materials platform is also promising for the development of THz QC sources potentially capable of room-temperature operation across the entire THz spectrum.

This work was partly supported by NSF under Grant ECS-0824116.

3. References

[1] M. Lee and M. C. Wanke, "Searching for a solid-state terahertz technology," Science **316**, 64 (2007).

[2] K. Feng, W. Streyer, Y. Zhong, A. J. Hoffman, and D. Wasserman, "Photonic materials, structures and devices for *Reststrahlen* optics," Opt. Express **23**, A1418 (2015).

[3] E. Bellotti, K. Driscoll, T. D. Moustakas, and R. Paiella, "Monte Carlo study of GaN versus GaAs terahertz quantum cascade structures," Appl. Phys. Lett. **92**, 101112 (2008).

[4] H. Machhadani, Y. Kotsar, S. Sakr, M. Tchernycheva, R. Colombelli, J. Mangeney, E. Bellet-Amalric, E. Sarigiannidou, E. Monroy, and F. H. Julien, "Terahertz intersubband absorption in GaN/AlGaN step quantum wells," Appl. Phys. Lett. **97**, 191101 (2010).

[5] W. Terashima and H. Hirayama, "Spontaneous emission from GaN/AlGaN terahertz quantum cascade laser grown on GaN substrate," Phys. Status Solidi C **8**, 2302 (2011).

[6] F. F. Sudradjat, W. Zhang, J. Woodward, H. Durmaz, T. D. Moustakas, and R. Paiella, "Far-Infrared intersubband photodetectors based on double-step III-nitride quantum wells," Appl. Phys. Lett. **100**, 241113 (2012).

[7] H. Schneider and H. C. Liu, *Quantum Well Infrared Photodetectors: Physics and Applications* (Springer-Verlag, Berlin 2007).

[8] H. Durmaz, D. Nothern, G. Brummer, T. D. Moustakas, and R. Paiella, "Terahertz intersubband photodetectors based on semipolar III-nitride quantum wells," Appl. Phys. Lett. **108**, 201102 (2016).