Terahertz range GaAs/AlGaAs quantum well photodetector

Mikhail Patrashin and Iwao Hosako

Abstract—**We have designed a GaAs/AlGaAs detector with a targeted peak frequency of 3 THz (100 μm) in an effort to extend the successful implementation of QWIP (Quantum Well Infrared Photodetector) arrays to the terahertz range. A simple multilayer structure has 18-nm GaAs QWs sandwiched between AlGaAs barriers with an Al alloy fraction of 2%. Despite the low Al content (2%), we obtained consistent results with MBE growth and could control the level of dark current and the impedance of fabricated devices within design-specific requirements. The level of dark current in optimized samples was a few μA/cm^{-2} and the detector observed response close to the designed detection wavelength. The responsivity of the detector was measured with a calibrated blackbody source. A responsivity of 13 mA/W at an electric bias of 40 mV and an operating temperature of 4 K was obtained.**

Index Terms—**Quantum well devices, Terahertz detectors**

I. INTRODUCTION

THERE have been continuing efforts in recent years to develop practical sources and detectors of terahertz radiation [1, 2, 3, 4, 5]. Most existing and emerging applications will utilize direct or heterodyne techniques of detection for terahertz imaging, spectroscopy and communications, and their successful implementation will depend on the availability of fast and sensitive multi-element detectors. There have traditionally been very limited choices of detectors with suitable characteristics in the terahertz region of the spectrum. Significant improvements have been achieved in the performance of mixers for heterodyne receivers below 1–2 THz, specifically, superconductor-insulator-superconductor (SIS) tunnel junctions and superconducting hot electron bolometers (HEBs). A number of photon detectors on the higher frequency side based on extrinsic semiconductors provide a viable option for some applications. Extrinsic Ge:Ga photodetectors, for example, offer sensitivities at least orders of magnitude better in the direct mode than superconducting bolometers operating at the same temperatures. Despite this progress, the significance of the terahertz region for practical imaging applications can only be fully attained with large-format multi-element detectors. It seems plausible, however, that evolutionary improvements and scaling of available technologies may not meet these requirements or could be prohibitively expensive, which would make alternative device concepts and materials worth considering.

One possible candidate that we are currently investigating is the GaAs/AlGaAs multi-quantum-well (QW) detector based on intersubband absorption in the quantum well. A suitable band structure is achieved with an appropriate width for the QW layer and a suitable composition for the alloy in the barrier layers.

Compound semiconductors, such as GaAs/AlGaAs, provide reliable and well-established material systems for designing quantum-well photodetectors in a targeted spectral range. These were primarily used for near- and middle-infrared devices until recently. The processing technology is fully mature and large-format infrared arrays with up to 1024×1024 pixels have been demonstrated [6]. The optimal design for a QW photodetector with a minimal level of dark current corresponds to a situation where the first excited state in the quantum well is aligned with the top of the barrier (bound to a quasi-bound configuration). If we apply a similar methodology to the range between 1–8 THz, the parameters of the QW structure will correspond to low aluminum fractions of a few percent (1–5%) and QW widths between 10–30 nm [7, 8].

II. DEVICE STRUCTURE

We have designed a GaAs/AlGaAs detector with a targeted peak frequency of 3 THz (100 μm) in an effort to extend the successful implementation of infrared QW arrays to the terahertz range (Fig. 1). A simple multilayer structure has 18-nm GaAs QWs sandwiched between AlGaAs barriers with an Al alloy fraction of 2%. The effect of different barrier widths and doping concentrations on the expected dark current and spectral response of the structure were numerically simulated, and several samples with various in-well doping concentrations (5×10^{16}–2×10^{17} cm^{-3}) and barrier widths (60 and 80 nm) were grown by MBE on semi-insulating GaAs substrates. X-ray diffraction, Scanning

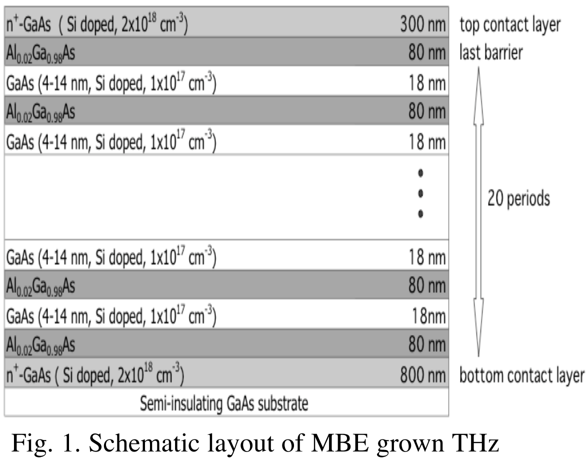

Fig. 1. Schematic layout of MBE grown THz quantum well photodetector structure.

M. Patrashin and I. Hosako are with the National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-0015, JAPAN (phone: +81-42-327-6939; fax: +81-42-327-6941; e-mail: mikhail@nict.go.jp).

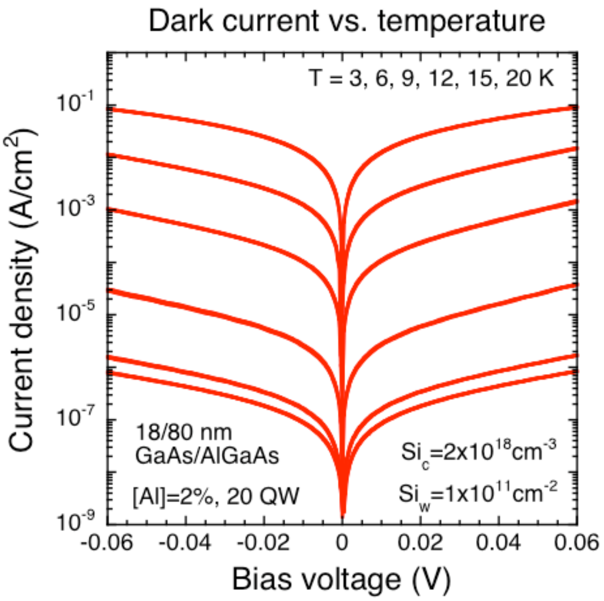

Fig. 2. Bias and temperature dependence of dark current.

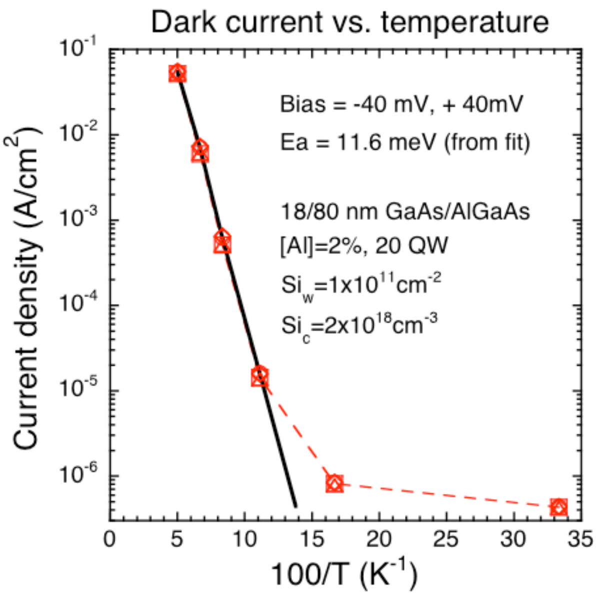

Fig. 3. Temperature dependence of dark current at 40 mV bias voltage. Below 8K the current flattens out at around 1μA/cm^2.

Electron Microscopy/Energy Dispersive Spectrometer (SEM/EDS), and Photoluminescence (PL) measurements were used to verify the composition, period, and energy-level structure of the samples. Only minor deviations from the designed parameters were observed.

The samples were processed into single-element square-shaped mesas with top and bottom ohmic contacts of different sizes using standard photolithography, wet etching, and thermal deposition. A simple grating coupler was implemented on top of the mesas to allow front-side illumination. Despite the low Al content (2%), we obtained consistent results with MBE growth and could control the level of dark current and the impedance of fabricated devices within design-specific requirements. Characteristics of 1mm×1mm detector with 50μm period grating are given below.

III. Device performance

The level of dark current in optimized samples was a few mA/cm^{-2} (Fig. 2, 3) and the detector observed response close to the designed detection wavelength (Fig. 4). Discrepancy between the expected spectrum and the experiment can be traced to a limitation of the model. Broad feature in the spectrum is probably caused by bound-to-continuum transitions, which were not considered in the present model. The responsivity of the detector was measured with a calibrated blackbody source. Responsivity of 13 mA/W at an electric bias of 40 mV and an operating temperature of 4 K was obtained by comparing current-voltage characteristics under different photon flux conditions. We believe that optimizing the in-well doping concentration further and improving the design of the grating coupler can produce even better performance.

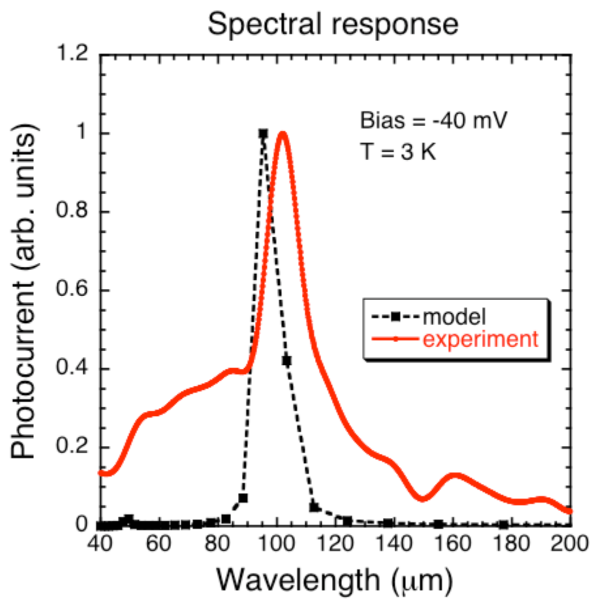

Fig. 4. Normalized spectrum of photoresponse compared with the result of numerical simulations. Detector oserved response close to the designed detection wavelength.

References

[1] R. Köhler, A. Treducucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Richie, R. C. Iotti, and F. Rossi, “Terahertz semiconductor-heterostructure laser”, Nature 417, 156 (2002).

[2] B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, “Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode”, Opt. Express 13, 3331 (2005).

[3] L. Ajili, G. Scalari, N. Hoyler, M. Giovannini, and J. Faist, “InGaAs–AlInAs/InP terahertz quantum cascade laser”, Appl. Phys. Lett. 87, 141107 (2005).

[4] H. Yasuda, I. Hosako, S. Miyashita, and M. Patrashin, “Terahertz electroluminescence from GaSb/AlAs quantum cascade laser”, Electron. Lett. 41, 1062 (2005).

[5] M. Fujiwara, T. Hirao, M. Kawada, H. Shibai, S. Matsuura, H. Kaneda, M. Patrashin, and T. Nakagawa, “Development of a gallium-doped germanium far-infrared photoconductor direct hybrid two-dimensional array”, Appl. Opt. 42 (12), 2166 (2003).

[6] S. D. Gunapala, S. V. Bandara, J. K. Liu, C. J. Hill, S. B. Rafol, J. M. Mumolo, J. T. Trinh, M. Z. Tidrow, and P. D. LeVan, “1024×1024 pixel MWIR and LWIR QWIP focal plane arrays”, Proc. SPIE Int. Soc. Opt. Eng. 5783, 789 (2005).

[7] H. C. Liu, C. Y. Song, A. J. SpringThorpe, and J. C. Cao, “Terahertz quantum-well photodetector”, Appl. Phys. Lett. 84, 4068 (2004).

[8] H. Luo, H. C. Liu, C. Y. Song, and Z. R. Wasilewski, “Background-limited quantum-well photodetetor”, Appl. Phys. Lett. 86, 231103 (2005).