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Dual color longwave InAs/GaSb type-II strained layer superlattice detectors

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HIGHLIGHTS

- Dual-band (LW/LWIR) InAs/GaSb T2SL detectors with barrier (pBp) architecture are reported.
- Quantum efficiencies of 37% (~11 μm band, −200 mV) and 25% (~9 μm band, +100 mV) are realized.
- MBE-grown ZnTe passivation is utilized to improve LWIR detector performance.

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ABSTRACT

We report on the design, growth, fabrication and characterization of dual-band (long-/long-wave infrared) type-II InAs/GaSb strained layer superlattice (T2SL) detectors with pBp architecture. Under operating the bias of −200 mV and +100 mV, quantum efficiencies of 37% (~11 μm band) and 25% (~9 μm band) were realized, respectively. To reduce the dark current in a dual-band T2SL detector, the effect of a "restoration" chemical etch treatment and ZnTe passivation on device performance were investigated.

1. Introduction

Multicolor detectors are desirable in a variety of infrared (IR) applications related to remote sensing and object identification. Bulk Mercury-Cadmium-Telluride (MCT) and quantum well infrared detectors (QWIPs) have been the dominant technologies for such applications [1,2]. In the past few years, IR detectors based on InAs/GaSb T2SLs have demonstrated extremely good performance including single [3,4] and dual-band imagers [5] owing to the basic material properties of T2SLs. In particular, the T2SL system facilitates suppression of interband tunneling [6] and Auger recombination [7] processes. The larger effective mass (~$0.04m_0$) in T2SL leads to a reduction of tunneling currents compared with MCT detectors of the same bandgap [8]. By optimizing the oscillator strength in this material system, a large quantum efficiency and responsivity can be obtained. Moreover, the commercial availability of substrates with good electro-optical homogeneity, and without large cluster defects, also offers advantages for the T2SL technology.

High performance InAs/GaSb T2SL detectors have been reported for mid-wave infrared (MWIR, 3–5 μm) [9–11], long-wave IR (LWIR, 8–12 μm) [12–14] , and very long wave IR (VLWIR, >12 μm) [15] spectral regions. Moreover, mega-pixel FPAs, i.e. FPAs of sizes up to 1024 × 1024 have been demonstrated [16,17]. Multiband T2SL structures were also realized, including short-wave IR(SW)/MWIR [18], MW/MWIR [19], MW/LWIR [20–22], LW/LWIR [23,24], and SW/MW/LWIR [25] detectors and focal plane arrays (FPAs).

The architecture of multiband T2SL cameras evolved from a vertical detector design with two 'back-to-back' InAs/GaSb T2SL photodiodes separated by a common ground contact layer [26–29] to more complicated barrier designs. In the former case, the absorption region for higher energy photons ("blue channel") is formed by the InAs/GaSb T2SL with a wider band-gap than the absorption region for lower energy photons ("red channel"). Since the thickness of the entire structure is lower than the typical total layer thickness of multicolor MCT FPAs (15 μm), the technological aspect of T2SL FPA fabrication is simplified. However, these detectors are

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prone to high diffusion and Shockley–Read–Hall (SRH) generation-recombination dark currents. The multiband detectors based on barrier designs (nBn, pBiBn, or pBp) are expected to reduce dark current due to the elimination of a depletion region in the detector heterostructure.

To realize multiband T2SL-based FPAs with high signal-to-noise ratio, the number of FPA pixels needs to increase with simultaneous scaling of the lateral dimensions of individual pixels. Then the FPA performance, with typical mesa dimensions of individual FPA pixels of 20 μm × 20 μm, is strongly dependent on surface effects due to a large pixel surface/volume ratio. Thus, methods for reduction and elimination of surface currents need to be developed. Despite the efforts of many research groups [30] devoted to the passivation of T2SL detectors, it still remains one of the essential limitations to be overcome in order for T2SL to be the technology of choice for high-performance imaging systems. With shifting of the detector operation wavelength into the LWIR region, passivation issues become even more challenging due to the reduced bandgap of the detectors. A number of studies have investigated the effect of dielectric passivation (with silicon-dioxide [31], polyimide [32], or photoresist [33,34]), overgrowth with larger bandgap material [35], and a buried architecture approach [36] on LWIR T2SL detector performance. Chalcogenide sulfur-based passivation (ammonium sulfide [37,38], zinc sulfide (ZnS) [39], thioacetamide (TAM) [40], and electrochemically (ECP) deposited sulfur coating [41]) forms a covalently bonded sulfur layer with group-III and -V atoms thus diminishing surface leakage currents and improving device performance. Recently, several research groups reported a "combined" approach for the passivation of T2SL detectors. For example, Zhang et al. [42] noticed that the anodic sulfide passivation combined with the SiO_2 significantly improved the performance of MWIR T2SL detectors. DeCuir et al. [43] found that the sulfide chemical treatment followed by the SU-8 treatment inhibits the formation of native surface oxides, satisfies dangling bonds, and prevents the sulfide layer from degradation over time.

However, there are certain drawbacks associated with common passivation methods. Dielectric passivation, though shown to be effective, presents challenges of developing high-quality films with low fixed and interfacial charge densities at process temperatures substantially lower than the InAs/GaSb T2SL growth temperature to prevent T2SL period intermixing. Moreover, native fixed charges present in the dielectric passivation layer can either improve or deteriorate the device performance [44], consequently, the dielectric passivation may not passivate the low band gap materials as effectively as high bandgap materials. MBE re-growth of a lattice-matched wide-bandgap III–V semiconductor layer on top of the exposed mesa sidewalls of a narrow-bandgap T2SL detector requires very careful surface cleaning prior the overgrowth procedure, which significantly complicates the fabrication process of detectors and FPAs.

Immersion in an ammonium sulfide solution may cause device performance degradation attributed to etching of the T2SL material by the passivation solution. E-beam deposition of ZnS may result in films with high fixed charge densities. The presence of fixed charges inside the passivation layer causes band bending at the edge of the semiconductor which forms leakage routes along the interface. Although ECP passivation is shown to be very effective, the uniformity of ECP coverage over larger areas is an issue. Moreover, poor stability of sulfur coatings produced by TAM and ECP passivations shows the necessity for a suitable capping layer to preserve good passivation quality in the long term. For these reasons we looked for a replacement of conventional sulfur-based passivations that would be close to the family of chalcogenides to retain the properties of ECP and provide better reliability and uniformity.

In this paper we present a InAs/GaSb T2SL dual-band (LW/LWIR) detector utilizing the pBp architecture. Moreover, the effectiveness of a novel ZnTe passivation treatment on the reduction of surface leakage currents in single-color InAs/GaSb T2SL detectors operating in the LWIR spectral region (100% cut-off wavelength of ~10.5 μm at 77 K) was also studied.

2. Experimental details

2.1. pBp dual-band structure design

The pBp LW/LWIR T2SL detector structure was designed using the empirical pseudopotential method (EPM) [45]. Implementation of the pseudopotential technique for simulation of the T2SL bandstructures may be outlined in several steps. First, the effective potential of the T2SL is calculated using the pseudopotential coefficients, also known as form factors [46], for the well (InAs) and barrier (GaSb or AlSb) materials. Next, eigenenergies and wavefunctions in the T2SL are evaluated and the radiative matrix elements for various transitions are calculated. Once bulk components are simulated, no special treatment or information is required to simulate the T2SL. This approach also incorporates coherent strain in the T2SL layers.

The pBp LW/LWIR (9 μm/11 μm) T2SL detector structure calculated by EPM was formed by InAs/GaSb T2SLs with layer thickness adjusted to reach the corresponding cut-off wavelengths separated by the InAs/AlSb T2SL barrier. The thickness of each absorber was 4 μm and the barrier was 100 nm thick. Top and bottom contacts were composed by a InAs/GaSb T2SLs with total thickness of 100 nm and 800 nm, respectively. The doping concentration was designed to be slightly p-type for the absorbers and barrier, $p = 1 \times 10^{16}$ cm^{-3}, and heavily p-type for the contacts, $p = 1 \times 10^{18}$ cm^{-3}. The corresponding band diagram is presented in Fig. 1. By changing the thickness of the InAs and GaSb T2SL constituent layers, the conduction band-offsets with respect to the absorber layer were minimized for both contact layers.

2.2. pBp dual-band material growth

The LW/LWIR pBp detector structure, schematically presented in Fig. 2, was grown on 3″ epi-ready GaSb n-type substrates by IntelliEPI, Inc. Several features of the LW/LWIR pBp structure have to be noted:

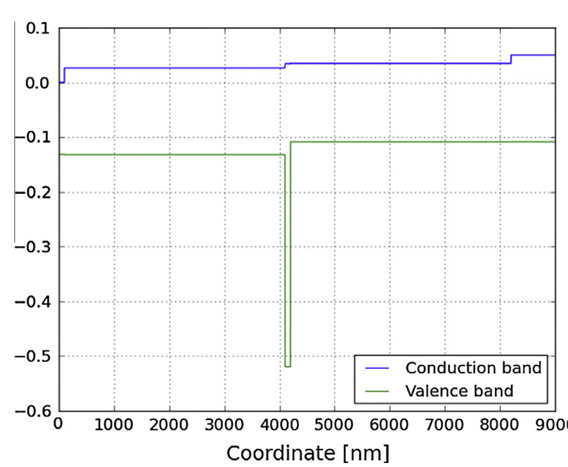

Fig. 1. Design of pBp detector with low-dark current architecture with minimized conduction band offsets. *Y*-axis has units of eV.