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PROGRESS ON TYPE-II INAS/GASB SUPERLATTICE (T2SL) INFRARED PHOTODETECTOR : FROM MWIR TO VLWIR SPECTRAL DOMAINS.

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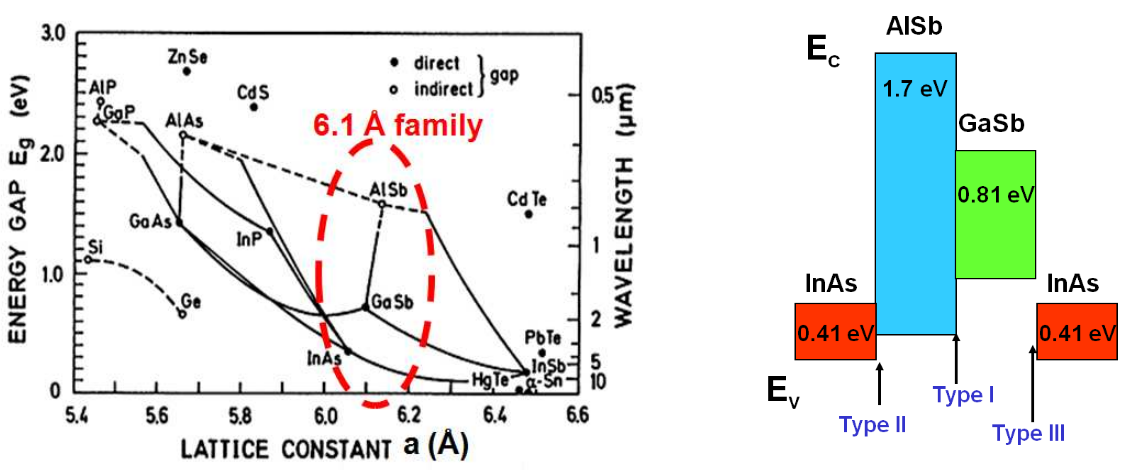
INTRODUCTION

Infrared photodetectors based on type-II InAs/GaSb superlattice (T2SL) material has been given a lot of attention this past decade, in particular by U.S. laboratories. Among the advantages of this material system, one can cite the possibility to span a large Infrared (IR) range (3µm to 30 µm) by tailoring the band-gap independently from the lattice constant, allowing addressing many applications by the same fabrication process and the realization of multi-color IR sensors for high performance imaging systems. Recently, the maturity of the growth of the quantum structure by molecular beam epitaxy (MBE) and progress on the processing resulted in the demonstration of high-performance mega-pixel focal plane arrays (FPA) in both the mid-wavelength (MWIR) and the long-wavelength (LWIR) infrared spectral bands [1]. Consequently, InAs/GaSb T2SL photodetector can be now considered as a new infrared technology which can be complementary to InSb, MCT or QWIPs technologies.

After some reminders on InAs/GaSb T2SL quantum structure properties, we present in this communication the results obtained by the IES laboratory, from Montpellier University, France, for photodiodes operating in the MWIR spectral domains. We then complete the paper by the main results reached by others laboratories for T2SL detectors operating from MWIR to VLWIR spectral ranges.

PROPERTIES of InAs/GaSb T2SL QUANTUM STRUCTURE

The 6.1 Angstrom (Å) family [2], made of GaSb, InAs and AlSb semiconductors, form a set of compounds that are closely lattice-matched to each other (Fig. 1a). With the use of InAs or GaSb as substrate, many innovative quantum structures can be build for active zone of infrared devices suitable for optoelectronic applications, such as laser diodes or photodetectors. This can be achieved thanks the strong flexibility of the 6.1 Å family, showing energy gap ranging, at 80K, from 0.41 eV (InAs) to 1.7 eV (AlSb) and heterostructures with type I, type-II or staggered type-II (type-III) band-lineups (Fig. 1.b).



(a) (b)

Fig. 1. (a) The energy gap versus the lattice constaostructure arent of compound semiconductors. The three semiconductors InAs, GaSb and AlSb, with lattice constant around 6.1 Å are called the "6.1 Å family". (b) Band lineups of InAs, GaSb and AlSb. The solid rectangles represent the forbidden band gap and the type of the offset between each binary heterostructure is specified

InAs/GaSb T2SL material was first fabricated by molecular beam epitaxy (MBE) and studied by Sai-Halasz *et al* [3] in the end of the 70's. Their pioneer works were motivated by the potentiality of this peculiar system for electronic and optical properties. Indeed, the InAs/GaSb heterointerface presents a specific type-III band alignment, where the conduction band of the InAs layer is lower than the valence band of the GaSb layer (Fig. 1b). Using this heterostructure to build a SL, the band gap of this periodic structure, determined by the energy difference between the first electron miniband C1 and the first heavy hole state V1, depends only on the layer thicknesses, in symmetric (same thickness of InAs and GaSb layers) or asymmetric (one of the two layers thicker than the other) configurations. Consequently, the SL structure can absorb between the V1 and C1 minibands (Fig. 2) a large IR radiation by tailoring the layer thicknesses and the period.

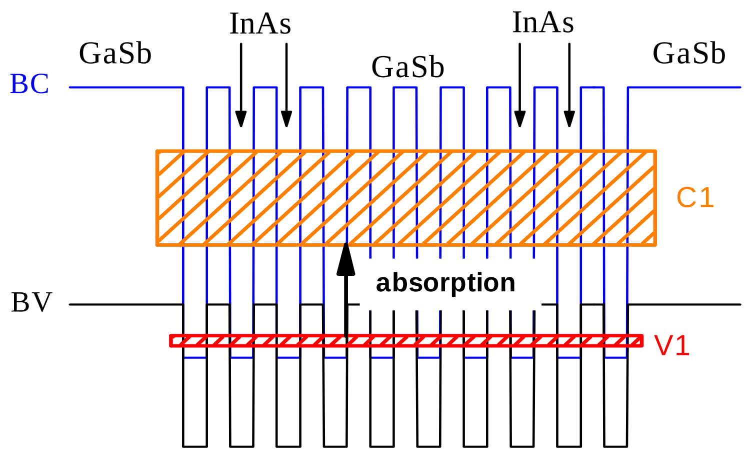
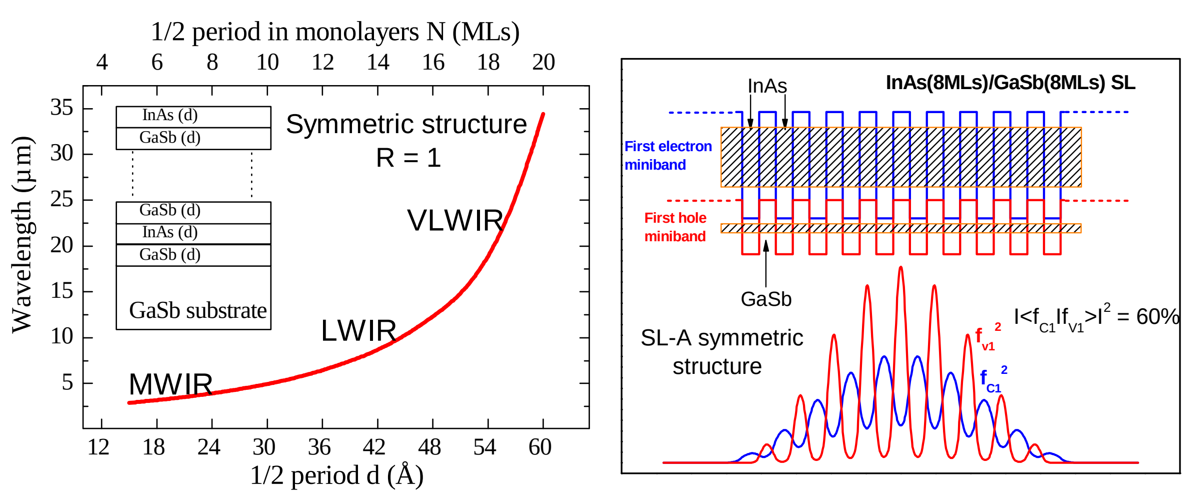


Fig. 2. Schematic view of the InAs/GaSb SL structure where the absorption phenomenon occurs between the fundamental electron (C1) and heavy hole (V1) minibands

To quantify the symmetric or asymmetric period design, we define the quantity R as the InAs to GaSb thickness ratio in each InAs/GaSb SL period : R = InAs/GaSb. In the case of R=1, Fig. 3 shows that the InAs/GaSb T2SL can address a wide range of IR wavelengths, from 3µm to 30µm, from the midwave infrared (MWIR) to the very longwave infrared (VLWIR).



(a) (b)

Fig. 3. (a) Calculated SL cut-off wavelength as a function of the 1/2 period thickness d (Å) or N (MLs) for the symmetric T2SL structure (R = 1). (b) Band diagram and first electron and hole minibands of the symmetric 8/8 T2SL. On the lower part, the fundamental electron miniband C1 and heavy hole miniband V1 probability densities are reported.

The symmetrical 8 monolayers (MLs) InAs/8 MLs GASb SL structure, suitable for the MWIR domain (Fig. 3a), exhibits a fundamental interminiband C1V1 wavefunction overlap values equal to 60%. Because of the indirect type-II band alignment, the electron is rather confined in the InAs layers while the fundamental heavy hole is somewhat located in the GaSb layers (Fig. 3b).

The InAs/GaSb T2SL was first proposed as active zone of IR photodetector (Fig. 4) by Smith and Mailhot [4] in the end of the 80's and the first demonstrations of photodetectors were made by Yang and Bennett [5] and Johnson *et al* [6] in the 90's, for devices operating in the MWIR and LWIR domains, respectively.

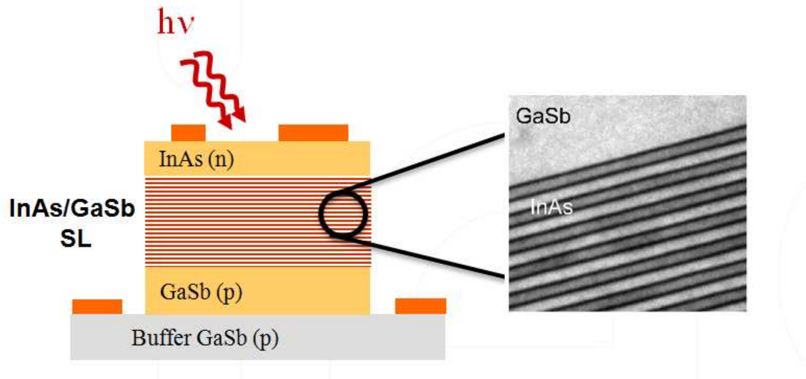


Fig. 4. Schematic view of the InAs/GaSb T2SL pixel pin photodiode on p-type GaSb substrate where the periodic InAs/GaSb structure was grown by MBE (In inset, Scanning Electron Microscopy (SEM) picture of the InAs-GaSb layers shaping the periodic superlattice).

T2SL MWIR PHOTODIODE AND FOCAL PLANE ARRAYS (FPA) AT THE IES LABORATORY.

At the IES laboratory of Montpellier University, T2SL structure for the MWIR spectral range are fabricated by MBE on GaSb substrate, with symmetrical (R=1) and asymmetrical (R≠1) period design. Fig. 5 displays the calculated SL energy gap at 77K for different thickness ratio R. In the case of symmetric structure (R=1), the InAs/GaSb SL structure can address the 3-5µm MWIR domain with layer thicknesses between 5 and 10 monolayers (MLs).

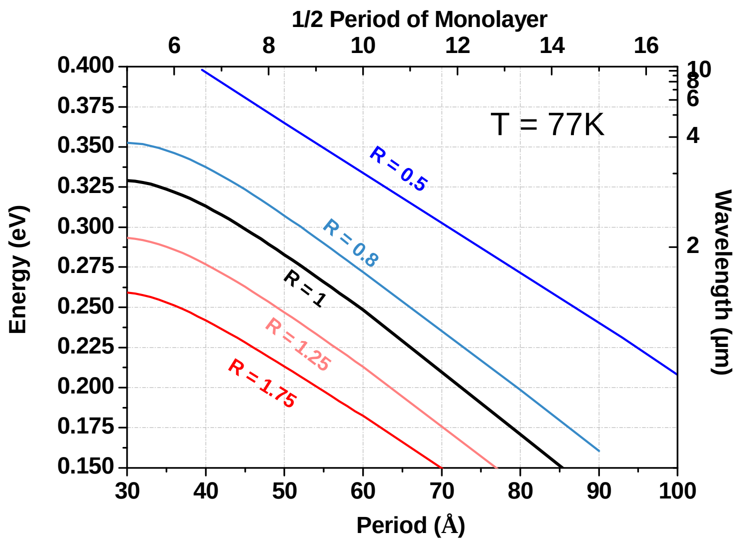


Fig. 5. Calculated SL bandgap at 77K as a function of the period thickness for different thickness ratio R = InAs/GaSb

Several T2SL structures were fabricated by MBE and the Fig. 6 reports photoresponse spectra of symmetrical structures having emission in the MWIR wavelength range. This figure highlights the ability of the T2SL to assign the 3-5µm spectral range by using the flexibility of the SL period [7].

In the case of an asymmetric (7/4) InAs/GaSb T2SL structure (R = 1.75), also called "InAs-rich" structure, with a cut-off wavelength of 5.5 µm at 77K (Fig. 7a) [8], Fig. 7b reports typical dark-current density J(V) curves of the diode where J value as low as $2x10^{-7}$ A/cm^2 and a R_0A value as high as $7x10^7$ Ω.cm^2 at 77K were recorded. These values are comparable with the ones of InSb photodiodes recently grown by MBE [9].

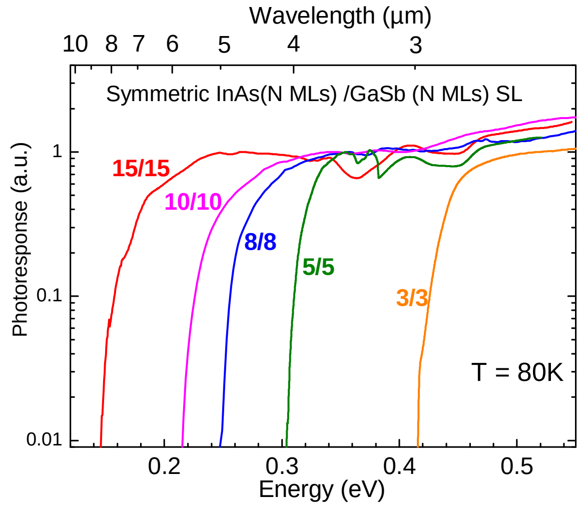


Fig. 6. Normalized photoresponse spectra of InAs (N) /GaSb (N) symmetrical SL MWIR detector structures with N = 3, 5, 8, 10 and 15 MLs. The spectra are recorded at 80 K.

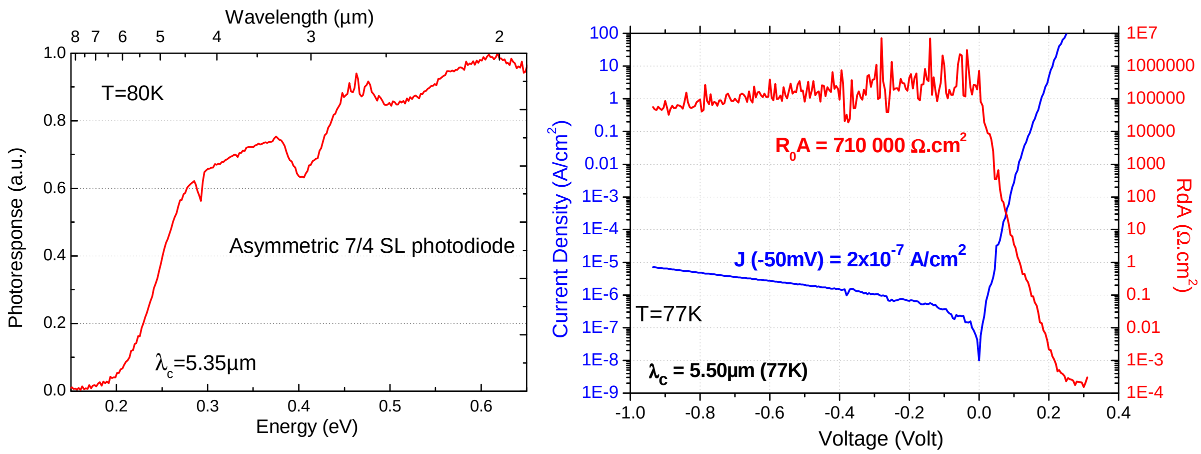


Fig. 7. Asymmetrical InAs (7) /GaSb (4) T2SL MWIR photodiode : (a) Normalized photoresponse spectrum at T = 77K, (b) dark current density and differential resistance-area product curves at 77 K.

To complete electrical characterization, noise measurements were performed under dark conditions at 77K on such MWIR diodes [10]. An example of the intrinsic noise spectrum obtained for a bias voltage of -0.2 V is displayed in Fig. 8. This figure clearly shows that the 1/f noise is present below 10 Hz. Above f = 10 Hz, we can observe white noise matching the theoretical Schottky noise.

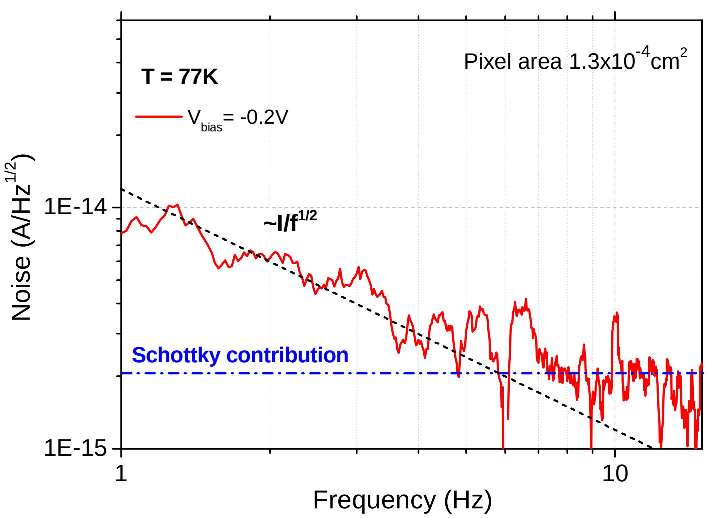
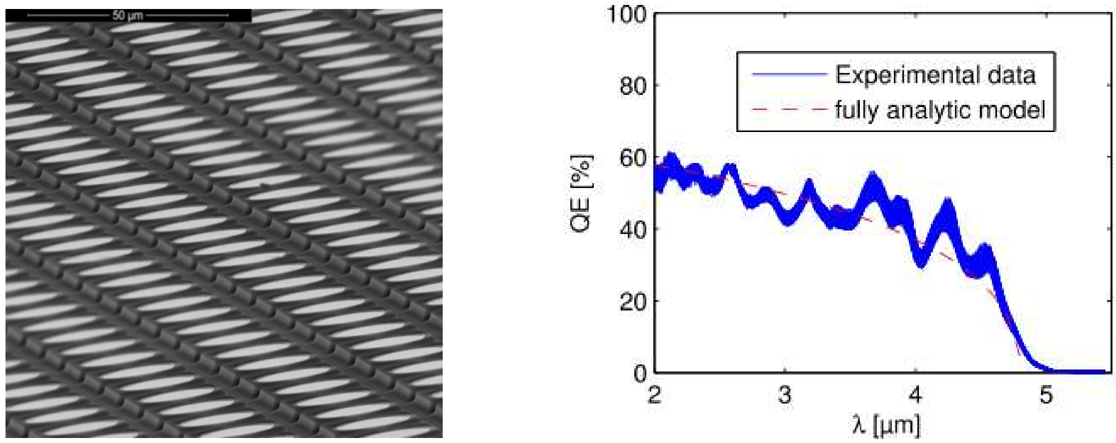


Fig. 8. Experimental intrinsic noise spectrum of T2SL MWIR photodiode.

Recently, a FPA has been fabricated by the collaboration between several French laboratories (IES, CEA, ONERA, and LPN), in the framework of the ANR project INTREPID [11]. The FPA, based on InAs-rich T2SL, was processed and then hybridized to a 320x256 pixels read out circuit with a pitch of 30µm (Fig. 9a). The pixels were wet etched and each pixel is a square shaped mesa of 24µm. No anti-reflection coating was applied and Fig. 9b displays the Quantum Efficiency measurements with a back-side illumination.



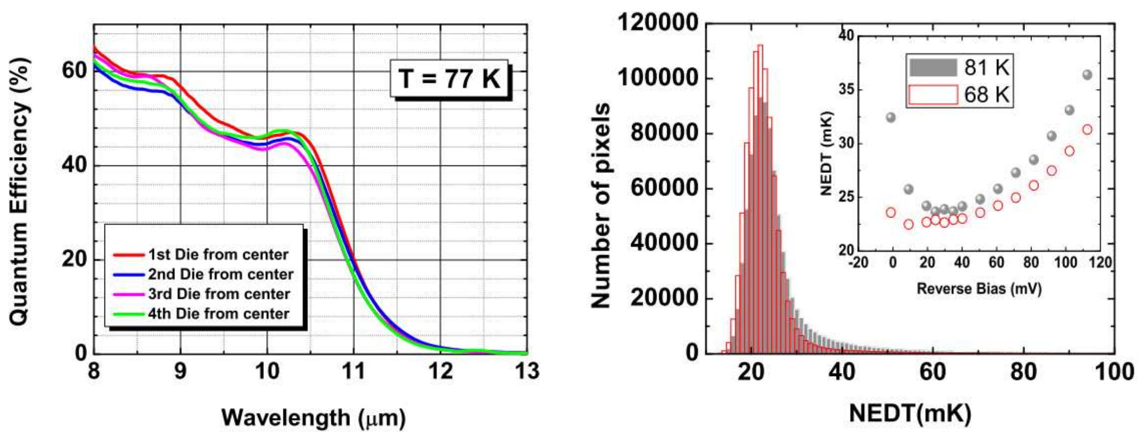
(a) (b)

Fig. 9. Asymmetrical 7/4 InAs/GaSb T2SL MWIR FPA : (a) SEM image of the array. The pitch of the array is 24µm, (b) QE spectra for 600 pixels of the FPA at U bias =-0.1 V and 77 K operating temperature.

High performance MWIR FPAs have been fabricated by several research groups. In particular, important developments have been made leading to a dual-color MWIR camera [12] and to raise the operating temperature of MWIR SL photodiode and FPAs with demonstration of human body imaging up to 170K [13].

T2SL PHOTODETECTORS FOR THE LWIR AND VLIWR SPECTRAL RANGES.

Concerning photodetectors and FPAs for the LWIR and VLWIR domains, most of the progresses have been achieved by the use of particular device designs [14, 15]. High performance 1k x 1k FPA has been fabricated [16] showing, on pixel photodiodes, a 50% cutoff wavelength of 11µm (Fig. 10a), a dark current density as low as 3x 10^{-4} A cm^{-2} and a differential resistance-area product at zero bias R_0A as high as 160Ω.cm^2 at 81 K. Noise equivalent temperature differences (NETD) of 23.6 mK and 22.5 mK have been measured for the megapixel FPA at 81K and 68K, respectively (Fig. 10.b).



(a) (b)

Fig. 10. 1k x 1k InAs/GaSb T2SL LWIR FPA :Results from Manurkar *et al* [16] (a) Quantum efficiency spectra of four single element dies across the 3" wafer at 77 K and 50 mV reverse bias showing a 50% cutoff wavelength at 11µm ; (b) NEDT histograms at 81 K (solid bars) and 68 K (open bars). Inset shows the NEDT variation with bias at both temperatures. *Published with permission of the authors*

By adjusting the thicknesses of constituent layers, the cut-off wavelength can reach the VLWIR domain. Fig. 11 shows the first demonstration, by the CQD laboratory from Northwestern University (USA), of T2SL having cut-off over than 30µm at low temperature (T=10K). Such demonstration highlights the potentiality of T2SL technology for space applications.

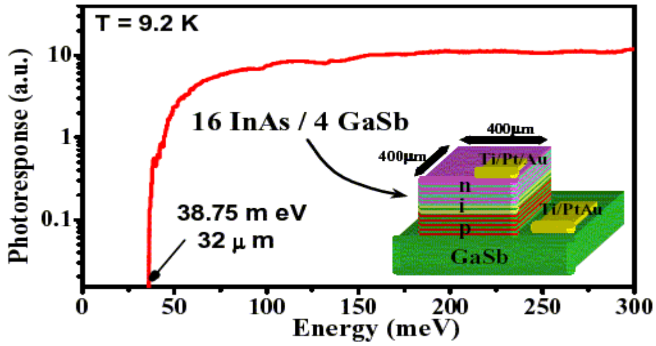


Fig. 11. Asymmetrical 16/4 InAs/GaSb T2SL photodiode fabricated by the CQD laboratory, exhibiting a 32µm cut-off at 9.2K. *Published with permission of the authors.*

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