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Type-II Superlattice Radiation Thermometer

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Abstract:
We report an evaluation of an InGaAs/GaAsSb type-II superlattice (T2SL) as a potential short-wave infrared (SWIR) detector for radiation thermometry. The multiple quantum well structure of the T2SL, as well as being lattice-matched to InP substrates, offers potentially low dark current compared with the current commercially available alternatives. The T2SL structure also offers tunability in the detection wavelength, therefore making it a versatile detector material. A T2SL structure was grown on an InP substrate using molecular beam epitaxy. It was fabricated and analyzed, with electrical and optical characterization taking place before the T2SL detector was evaluated for radiation thermometry. Temperature dependent radiation thermometry measurements were performed between blackbody furnace temperatures of 250 and 630 ^{0}C. The T2SL-thermometer showed good linearity over the temperature range measured with an effective wavelength of 2.56 µm. Analysis of the results suggests areas of improvement required in both the dark current and responsivity of the T2SL. With further development work on the T2SL material, it should be possible to optimize a T2SL detector for radiation thermometry capable of measuring down to room temperature.

Key words: InGaAs/GaAsSb type-II superlattice, infrared detector, short-wave infrared, radiation thermometry, radiation thermometer.

Introduction

Radiation thermometer performance and the applications to which they can be used are ultimately limited by the available detector technology. Within the short-wave infrared (SWIR) atmospheric window, operation up to 1.6 µm can be achieved with low dark current and moderate cost using Ge or InGaAs detectors [1,2]. However, as the cut-off wavelength increases up to 2.5 µm, the options become more expensive. Strained InGaAs and HgCdTe (MCT) are options [3,4], but both technologies have growth challenges which make them difficult to produce and therefore leading to their increased expense. Both technologies also suffer from high dark currents, which limit their performance or dictate the need for cooling. Cheaper alternatives, such as thermopiles and PbS, are less sensitive, prone to signal drift and are inherently slow to respond.

A highly promising detector technology in the SWIR is the InGaAs/GaAsSb type-II superlattice (T2SL), which offers the potential of low dark current as well as tunability in its detection wavelength [5,6]. The detector structure consists of thin layers of alternating InGaAs and GaAsSb material, which create a multiple quantum well structure. The layers are so thin that they are of the order of the de Broglie wavelength of the carriers, leading to the formation of mini-bands within the structure. Electrons and holes couple in neighbouring wells, resulting in wavefunction overlap. Tunnelling assisted transitions occur across the layer interfaces, resulting in a bandgap smaller than either of the constituent layers, as shown in Fig. 1. This therefore results in a longer cut-off wavelength, allowing detection beyond 2.5 µm. The material system is lattice-matched to commercially available InP substrates, which enables the detectors to be grown without introducing excess strain to the structure. This therefore results in longer wavelength detection without the addition of strain induced dark current.

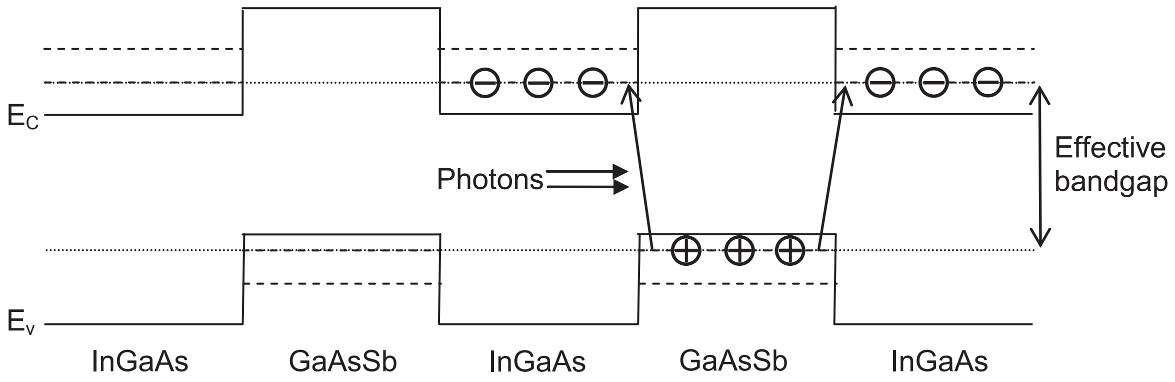

Fig. 1. Band diagram of InGaAs/GaAsSb T2SL showing band alignment, effective bandgap and carrier transition upon photon absorption.

In this work we report an assessment of an InGaAs/GaAsSb T2SL detector for use in a radiation thermometer. The detector was characterised electrically and optically before being tested in a radiation thermometer. A dark current of 56 µA was measured at -1 V, with an unbiased responsivity of 0.1 A/W which increased to 0.6 A/W under a bias voltage of -5 V. The unbiased detector was inserted into a transimpedance amplifier (TIA) circuit, with the output voltage measured as a function of furnace temperature to assess the detector's performance in a radiation thermometer. The detector showed good linearity with furnace temperature, with an effective wavelength of the T2SL-thermometer found to be 2.56 µm. Analysis suggested the material growth quality needs to be improved in order to enable its responsivity to be maximised at 0 V along with reducing the dark current. By combining this with an optimised anti-reflection (AR) coating, a responsivity of 1.2 A/W should be possible, therefore enabling the development of a T2SL-thermometer capable of measuring down to room temperature.

Experimental Methods

The T2SL photodiode wafer was grown using molecular beam epitaxy, as shown schematically in Tab. 1. For the detectors used in this analysis, mesas diodes of 1 mm in diameter were fabricated using standard photolithography and wet etching techniques, although no anti-reflection coating was deposited. The detector die were cleaved and packaged onto transistor outline style TO-5 headers for characterization and assessment for radiation thermometry. Growth, fabrication and packaging took place at the UK EPSRC National Centre for III-V Technologies at the University of Sheffield.

Tab. 1: T2SL detector wafer structure

Function	Material and thickness (nm)	Doping (cm^{-3})
p^+ contact	$In_{0.53}Ga_{0.47}As$ 20 nm	1×10^{19}
p^+ cladding	$In_{0.53}Ga_{0.47}As$ 500 nm	2×10^{18}
i	$In_{0.53}Ga_{0.47}As$ 45 nm	Undoped
i absorber	5 nm $In_{0.53}Ga_{0.47}As$ / 5 nm $GaAs_{0.51}Sb_{0.49}$ 1500 nm	Undoped
i	$In_{0.53}Ga_{0.47}As$ 50 nm	Undoped
n^+ cladding	$In_{0.53}Ga_{0.47}As$ 500 nm	2×10^{18}
n^+ substrate	InP	1×10^{19}

The T2SL detector was characterized both electrically and optically. Electrical characterization involved assessment of dark current and shunt resistance using a TIA circuit. Optical characterization involved measurement of spectral response using a monochromator, with a 2.004 µm distributed feedback laser used to measure the responsivity. The TIA circuit was also used to evaluate the T2SL for radiation thermometry.

The TIA circuit comprised of a Texas Instruments OPA637 operational amplifier, a 910 kΩ resistor and a 6.8 nF capacitor. This resulted in a radiation thermometer with an RC time constant of 6 ms. The rise time was intended to be representative of the many commercial thermometers that have time constants between 1 and 10 ms. Radiation thermometry measurements were performed at an operating voltage of 0 V in order to minimize the effect of dark current on the thermometer noise performance. The circuit was biased for measurement of dark current.

Temperature dependent radiation thermometry measurements were carried out by measuring the output of the TIA as a function of black body furnace temperature. A lens was placed 80 mm from the detector in order to focus the emitted radiation onto the detector. Assessment took place with a 1.9 to 2.7 µm band-pass filter placed between detector and furnace in order to minimize the effect of photon absorption outside of the desired wavelength band. Finally, a stability test took place to measure any detector output drift over time by sighting the detector at a furnace and data logging the output.

Results and Discussion

Dark current measurements were carried out as a function of bias voltage, as shown in Fig. 2. A dark current of 56 µA was measured at -1 V, whilst differentiating and taking the inverse at 0.1 V yielded a shunt resistance of 1750 Ω. The -1 V dark current and shunt resistance of a Hamamatsu G8373-01 strained InGaAs detector are 15 µA and 3000 Ω, respectively. Therefore, there is room for improvement for the T2SL. Additionally, as the theoretical dark current of lattice-matched T2SL material is lower than that of the strained InGaAs, there is clearly much to be done to achieve optimized T2SL dark current.

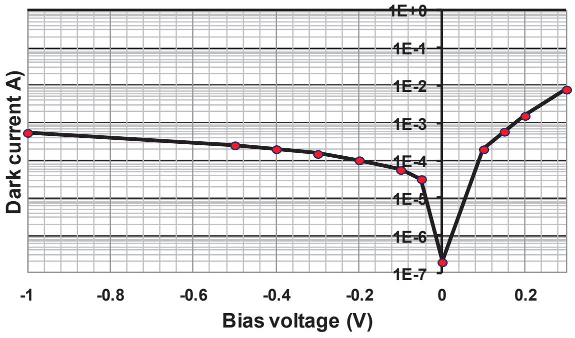

Fig. 2. Dark current for T2SL as a function of bias voltage

The T2SL's responsivity at 2.004 µm was measured to be 0.53 A/W at -5 V. Combining this with the T2SL's spectral response showed that a peak responsivity of 0.6 A/W could be measured at 2.24 µm. The Hamamatsu strained InGaAs detector has a peak responsivity of 1.3 A/W at 2.3 µm for 0 V operation. Again, this is better than the T2SL, indicating that optimization is required.

The target temperature dependence of the T2SL-TIA output was assessed between 250 and 630 °C, as shown in Fig. 3(a). In order to assess the linearity of the T2SL-TIA output, the log of the output voltage was plotted as a function of inverse temperature, as shown in Fig. 3(b). The gradient of this plot also enables calculation of the effective wavelength of the detector over the measured temperature range, and can be derived from Wien's Law [7]. This essentially is defined as the weighted average wavelength at which the thermometer operates.

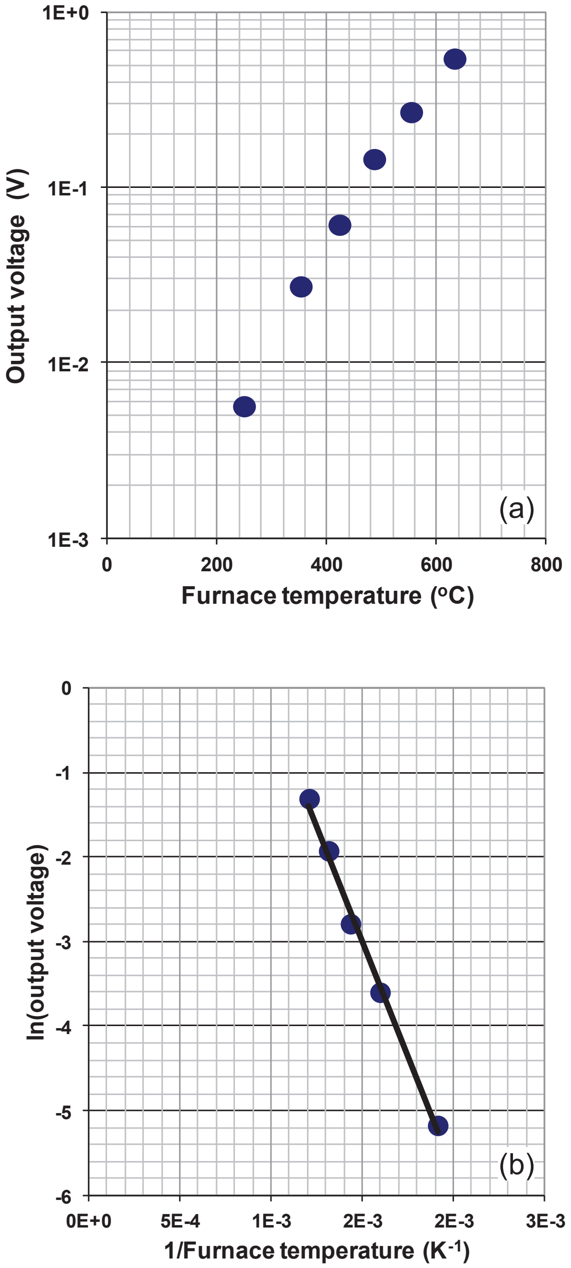

Fig. 3. (a) T2SL-TIA output with furnace temperature and (b) linearity of detector between 250 and 630 °C.

The highly linear response shown in Fig. 3(b) indicates that the T2SL has a good level of linearity over the temperature range measured. This is highly promising and essential for use in radiation thermometry. From these results, an effective wavelength of 2.56 µm could be calculated. Due to the presence of a window in the atmospheric water absorption spectrum between 2 and 2.6 µm, this effective wavelength makes the T2SL useful for low temperature SWIR measurements.

By taking the output data, the responsivity was re-calculated to be 0.1 A/W. Comparing this against the previously calculated responsivity of 0.6 A/W, there is a clear drop. However, it should be noted that the 0.6 A/W responsivity was measured at -5V, implying that the detector requires biasing in order to operate at its maximum responsivity. This requirement for biasing has also been observed by other authors [5] and is believed to be caused by a high level of background doping within the absorber layer. This doping is unintentional impurities which have been introduced during the epitaxial growth. This therefore limits the depletion region width, which is a high electric field region within the structure. This field acts to force carriers out of the depletion region and out of the photodiode, therefore making it the region of greatest carrier collection within the detector. By limiting the size of this region, carrier collection is also limited. A bias voltage is required to increase the depletion region, increase the carrier collection and therefore increase the responsivity. It would be straightforward to bias our T2SL detector for temperature measurement, however a fully optimized photodiode will provide lowest noise performance at 0 V.

Drift free measurement is essential for unchopped radiation thermometer operation. Optical choppers are sometimes required to compensate for this drift as the operating wavelength moves towards longer wavelengths; narrower bandgap material systems result in higher dark current. The T2SL-TIA output was measured over a period of 100 seconds whilst sighted at a 300 ºC furnace. Fig.4 shows the detector photocurrent drift over this period.

The drift in the photocurrent is less than 1 nA, which corresponds to ±1.5 K if converted to a temperature measurement. This is a relatively large drift, although an estimated furnace drift of ±0.5 K should also be factored in. There is clearly development work required to reduce this drift.

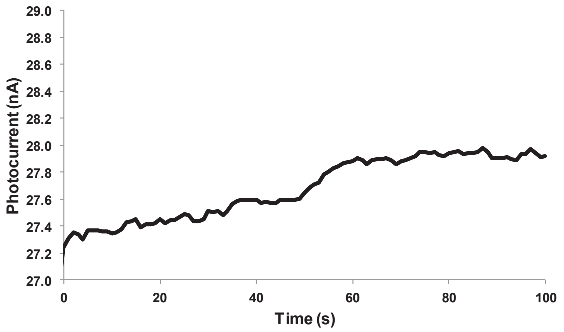

Fig. 4. T2SL photocurrent drift over 100 second period whilst sighted at 300 ºC furnace.

These combined results indicate the potential of the InGaAs/GaAsSb T2SL for radiation thermometry, however there are clearly areas of improvement required in order to reduce the dark current and increase the responsivity at 0 V. The higher dark current in comparison with a strained InGaAs detector is believed to be due to a high level of background doping, whilst the reduced responsivity is due to insufficient photon absorption and lack of AR coating. Reduction in the dark current would be expected by improved epitaxial growth leading to lower background doping. This reduction in background doping would also lead to increase in the depletion width. With full depletion at 0 V, unbiased operation would be possible. In order to increase photon absorption, a thicker absorption region should be grown by incorporating more layers. Due to the layers being lattice-matched to the InP substrate, this should be possible without adding strain to the structure. If all this were combined with an optimized AR coating, a responsivity of 1.2 A/W at 0 V is a distinct possibility. The dark current would also be expected to be lower than for a strained InGaAs detector due to the T2SL's lattice-matching to the InP substrate.

Assuming this improved responsivity of 1.2 A/W, a theoretical calculation of the T2SL-TIA output as a function of furnace temperature is shown in Fig. 5 along with a calculation for 0.1 A/W responsivity. The calculations for both responsivities assume an effective wavelength of 2.56 µm.

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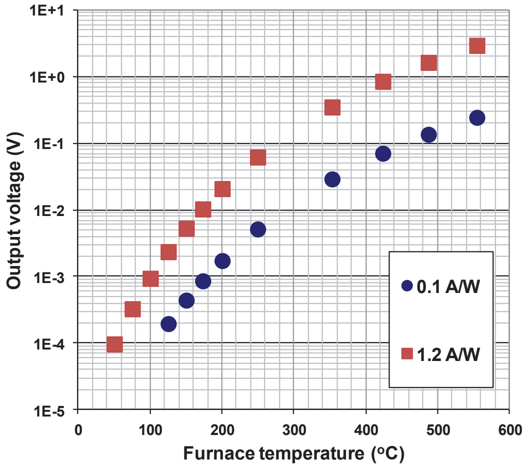

Fig. 5. Output voltage of T2SL-thermometer for current detector along with expected output voltage for optimized T2SL-thermometer.

For the current responsivity of 0.1 A/W, we would expect a thermometer containing a T2SL to measure down to 125 °C. However, with an optimized detector with a responsivity of 1.2 A/W and lower dark current, it could be possible to measure down to approaching room temperature. A lower dark current would reduce the noise floor and therefore allow the thermometer to measure weaker signals corresponding to lower target temperatures.

Conclusion

We have presented an InGaAs/GaAsSb T2SL as a potentially viable detector for use in SWIR infrared thermometry. The detector demonstrated good linearity over the temperature range measured, with an effective wavelength of 2.56 µm. Further device optimization is required, but a fully optimized T2SL with a responsivity of 1.2 A/W and lower dark current could possibly measure down to room temperature.

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