Evidence of carrier localization in InAsSb/InSb digital alloy nBn detector

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ABSTRACT

Recently we have demonstrated a novel method of extending the cut-off wavelength of InAsSb nBn detectors, by incorporating a series of monolayers of InSb. Here we study photoluminescence and minority carrier lifetime of this InAsSb/InSb digital alloy. While increasing temperature from 15 K to 40 K we show a 14 meV blue shift of the photoluminescence peak energy and a decrease in lifetime. This deviation from the expected Varshni empirical relation indicates strong carrier localization. We contrast to photoluminescence and lifetime results in bulk InAsSb. We discuss implications of this localization for design of digital alloy InAsSb/InSb nBn detectors.

Keywords: infrared detectors, mid-wavelength infrared (MWIR), InAsSb/InSb photodiodes, nBn, carrier localization

1. INTRODUCTION

Mid-wave infrared (MWIR) detectors offer promise for future NASA earth science missions, covering the crucially important 3–5 μm atmospheric windows. III-V nBn detectors[1] are one of the most important realizations of this technology, consisting of a wide bandgap barrier layer between n-type top contact and absorber layers. This unipolar barrier suppresses dark current due to Shockley–Read–Hall recombination,[1] by blocking the flow of majority carriers (in this case, electrons). However the wavelengths which can be covered by the resulting detector are constrained by the bandgaps, band alignments, and by lattice-matching to the substrate wafer. These constraints limit the materials which can be used. One previous successful architecture has been the InAsSb/AlAsSb absorber-barrier combination, but InAsSb is limited to cut-off wavelengths of $\lambda_c = 4$ μm.

In prior work,[2,3] we have demonstrated a novel method of extending the cut-off wavelength of InAsSb by creating a "digital alloy" incorporating monolayers of InSb into the grown InAsSb. This has extended the cut-off wavelength to $\lambda_c = 4.6$ μm at $T = 200$ K, allowing detection of the crucially important CO_2 absorption line at 4.26 μm. A 2 μm thick absorber fashioned from this material demonstrated quantum efficiency of $QE = 0.45$ with no antireflection coating, with a dark current density of 5×10^{-6} A/cm^2 at $T = 150$ K, operating at the background-limited infrared photodetection (BLIP) criterion. It demonstrated a minority carrier lifetime of $\tau = 500$ ns, as measured by the optical modulation response (OMR) technique.[4]

Minority carrier lifetime is often regarded as an important proxy for the performance of infrared detectors,[5–7] as it allows for greater carrier collection efficiency and suppresses dark current.[8] However, recent work on related InAsSb/InAs superlattices[9] has demonstrated the importance of considering carrier localization in this picture. Such carrier localization can lead to a dramatic increase in lifetime[10–14] that is not accompanied with a concomitant increase in detector performance, because the localized states have low mobility.[10]

2. PRIOR WORK

It has been widely observed that the bandgap of semiconductors obeys an empirical relation with temperature known as the Varshni relation:[15]

$$E(T) = E(0) - \frac{\alpha T^2}{\beta + T}, \tag{1}$$

where $E(T)$ is the energy gap at temperature T, and α and β are the so-called Varshni thermal coefficients.

In numerous other works,[9–14] charge localization has appeared as a deviation from this relation, with the photoluminescence peak showing blueshift with temperature at low temperatures. It is hypothesized that this is because while at high temperatures the primary transitions are between higher-energy distributed states, at low temperatures the primary transitions begin to be between lower-energy localized states. In some cases[10,11] this shift is made particularly obvious with the appearance of a second photoluminescence peak.

This anomalous blueshift is also accompanied by a rapid rise in minority carrier lifetimes. This is hypothesized to be caused by poor mobility of the localized states.[10–14] It is also accompanied by an increase in the full-width half maximum (FWHM) of the photoluminescence peak; this is due to the effective decoupling of the different localization centers, leading to different Fermi energies at each.[9]

3. EXPERIMENT

The fabrication of the two samples used in this experiment has been described previously;[2,3] here we provide a simplified summary. The two samples consist of a bulk InAsSb nBn sample and a digital alloy InAsSb/InSb nBn sample. Both samples were grown in a Veeco Applied-Epi Gen III molecular beam epitaxy chamber on low n-type doped (1×10^{17} cm^{-3}) GaSb substrate.

The bulk InAsSb sample consisted of an absorber layer of 2.5 μm of $InAs_{0.915}Sb_{0.085}$, unintentionally n-type doped at approximately 1×10^{16} cm^{-3}. On top of this are a barrier layer of 100 nm of $AlAs_{0.10}Sb_{0.90}$, also unintentionally doped, and a top layer of 100 nm of $InAs_{0.915}Sb_{0.085}$ n-type doped at 6×10^{17} cm^{-3} for the top 70 nm.

The InAsSb/InSb digital alloy sample consisted of an absorber layer of 2 μm of alternating layers of 14 monolayers of $InAs_{0.915}Sb_{0.085}$ and 1 monolayer of InSb, unintentionally n-type doped at approximately 1×10^{16} cm^{-3}. Its total period is 4.5 nm. On top of this are a barrier layer of 100 nm of $AlAs_{0.10}Sb_{0.90}$, also unintentionally doped, and a top layer of 100 nm of $InAs_{0.915}Sb_{0.085}$ n-type doped at 5×10^{17} cm^{-3} for the top 50 nm.

The photoluminescence and minority carrier lifetime of these samples was measured while illuminated by a 643 nm wavelength diode laser. Measurements were taken in a flow cryostat at temperatures ranging from 10 K to 200 K. Photoluminescence spectra were acquired with a Bruker IFS66v Fourier transform infrared (FTIR) spectrometer. Minority carrier lifetime was measured using the optical modulation response (OMR) technique.[4] The full details of these techniques have been published previously.[16]

4. ANALYSIS

Fig. 1 shows the peak energy of the photoluminescence peaks for bulk InAsSb and the InAsSb/InSb digital alloy. These measured values are shown as dots for temperatures ranging from 10 K to 200 K. A fit to the Varshni relation (Eqn. 1) is shown as a solid line. For the bulk InAsSb, all points have been included in the fit, while for the InAsSb/InSb digital alloy, the points at temperatures of 30 K and below have been excluded. The digital alloy shows an anomalous blueshift between 30 K and 35 K of 14 meV, deviating from the standard Varshni relation, as seen in other carrier-localized systems.[9–14]

Fig. 2 shows the measured full-width half maxima (FWHMs) of the photoluminescence peaks for bulk InAsSb and the InAsSb/InSb digital alloy. In general both show an almost monotonic upward trend with increasing temperature, however the digital alloy sample shows a spike in FWHM at temperatures of approximately 25 K to 35 K. This is consistent with the hypothesized decoupling of the localized states from each other, leading to multiple Fermi distributions.[9]

Fig. 3 shows the measured minority carrier lifetimes for both the bulk InAsSb sample and the InAsSb/InSb digital alloy sample for temperatures ranging from 15 K to 200 K. Both samples are relatively flat above 35 K, but below this the digital alloy sample shows a rapid spike in lifetime, rising from 670 ns to 1400 ns and then ultimately reaching a lifetime of 1800 ns at 15 K. This rapid rise in lifetime is consistent with that observed in other examples of carrier localization.[9–14]

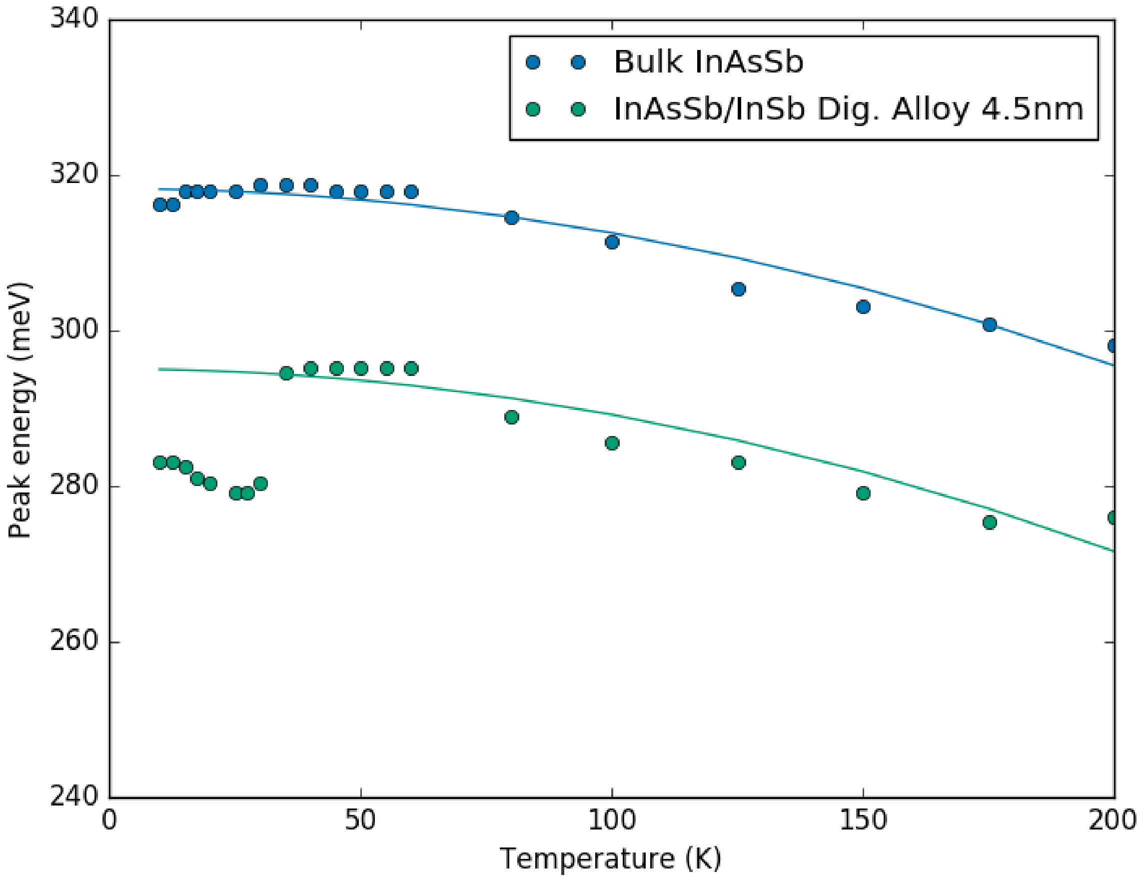

Figure 1. The measured peak energy of the photoluminescence peaks for bulk InAsSb (blue dots) and the InAsSb/InSb digital alloy (green dots) are shown for temperatures ranging from 10 K to 200 K. Fits for both samples to the Varshni relation (Eqn. 1) are shown as solid lines. For the digital alloy sample, the points at temperatures of 30 K and below show deviation from the standard Varshni relation consistent with carrier localization. These points have been excluded from the fit.

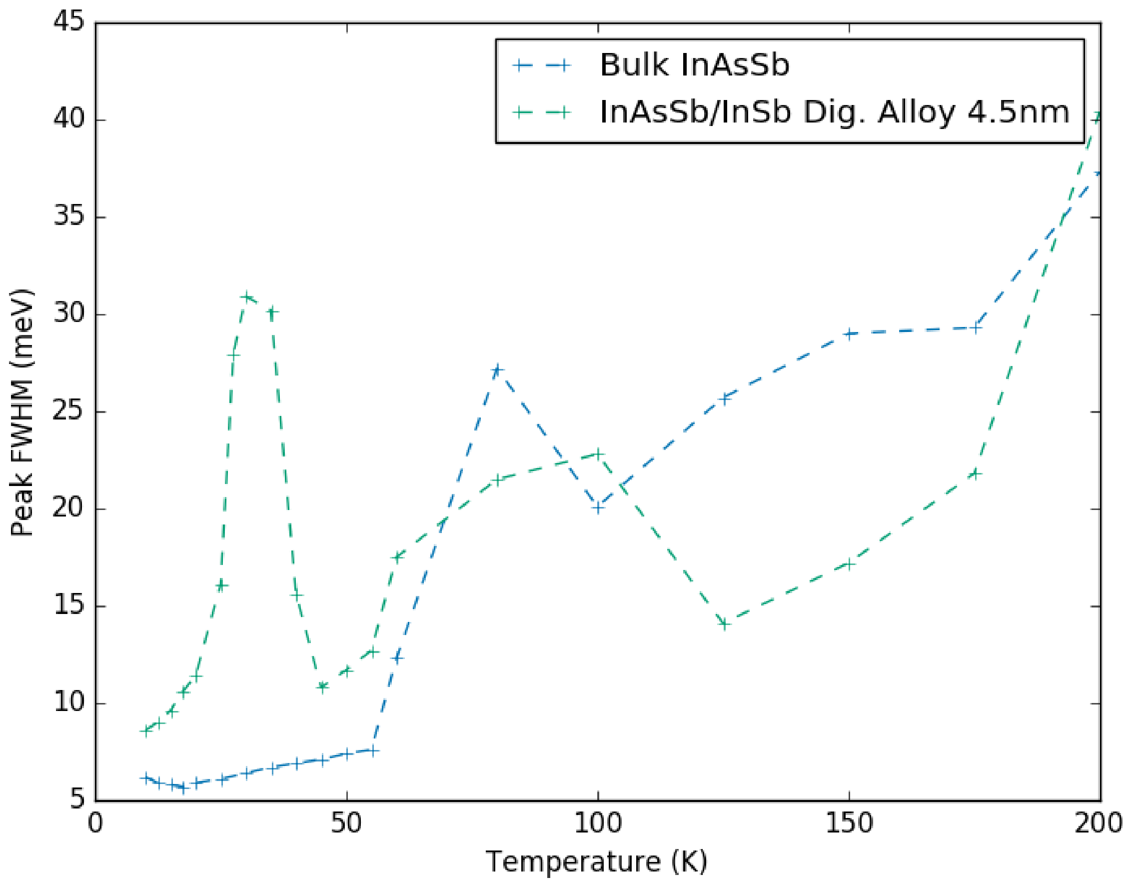

Figure 2. The measured full-width half maxima (FWHMs) for bulk InAsSb (blue) and the InAsSb/InSb digital alloy (green) are shown for temperatures ranging from 10 K to 200 K. Both show an almost monotonic upward trend, however the digital alloy shows a large spike in FWHM between temperatures of 25 K and 35 K.

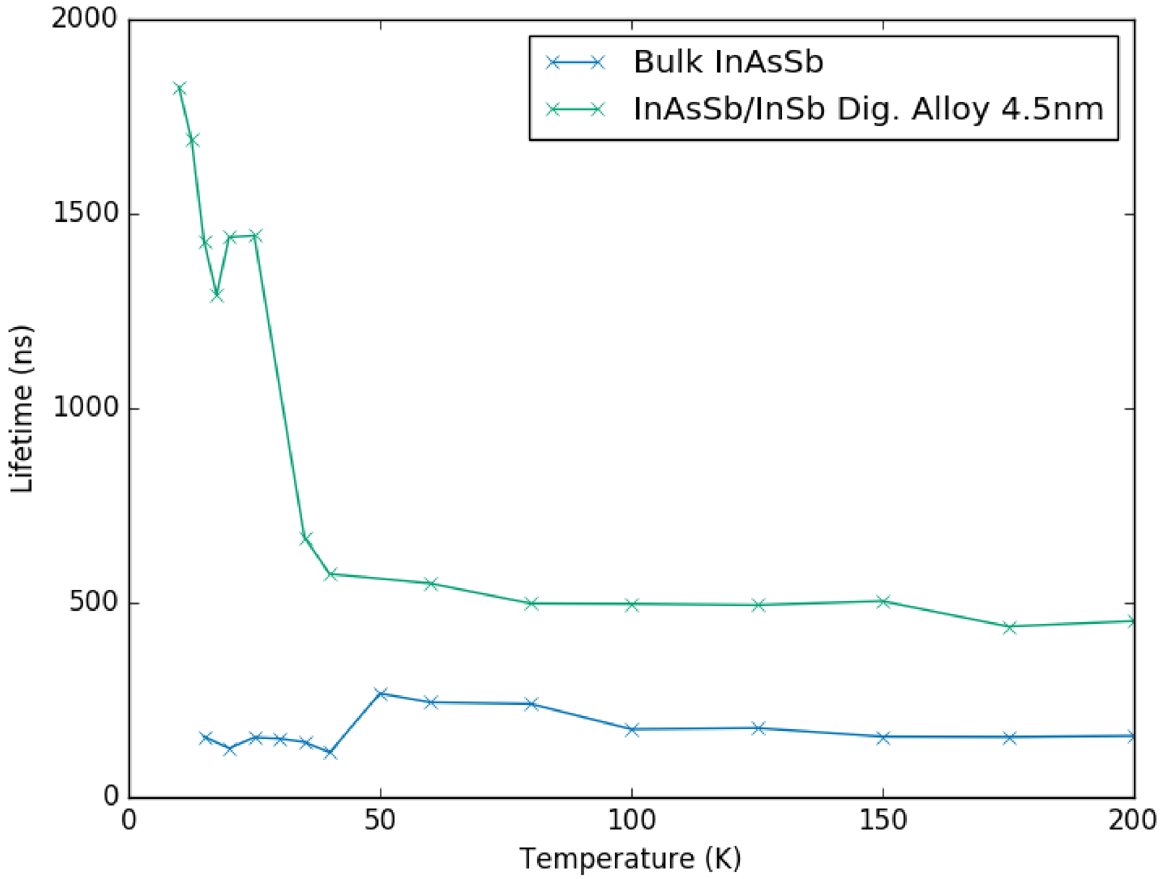

Figure 3. The measured minority carrier lifetimes are shown for bulk InAsSb (blue) and the InAsSb/InSb digital alloy (green), as measured by the optical modulation response (OMR) technique, for temperatures ranging from 15 K to 200 K. Both are relatively flat at 35 K and above, but the digital alloy shows a rapid rise in lifetime as temperature falls below 35 K.

5. CONCLUSION

In conclusion, we have presented the a study of the photoluminescence characteristics and minority carrier lifetime of two samples: a bulk InAsSb nBn photodetector, and an InAsSb/InSb digital alloy nBn photodetector. We have looked at temperatures from 10 K to 200 K and have observed some broad trends. First, the photoluminescence peak of the digital alloy sample displays anomalous blueshifting at temperatures below 35 K, seemingly in conflict with the Varshni empirical relation. Second, the width of the photoluminescence peak of the digital alloy sample, as measured by FWHM, spikes from 25 K to 35 K. Finally, the minority carrier lifetime of the digital alloy sample, as measured by the optical modulation response (OMR) technique, rapidly rises as temperature falls below 35 K.

All of this is consistent with prior work demonstrating carrier localization in other semiconductor systems.[9–14] This demonstrates the continued importance of being aware of carrier localization. This localization can mislead, causing minority carrier lifetime to rise without a concomitant rise in photodetector performance. Though this sample does not show localization above 35 K, prior examples have shown the effect even above 100 K,[11,13,14] at realistic operating temperatures for infrared photodetectors.

At this point it is not possible to say with certainty what the cause of the carrier localization in the digital alloy is, though suggested causes in other works include monolayer fluctuations in the thickness of the layers, as well as fluctuations in alloy composition and interface roughness. Further work will be necessary to narrow down the cause.

ACKNOWLEDGMENTS

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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