Monolithic Semiconductor Plasmonic Devices

L. Nordin, A. Briggs[1], E. Simmons[2], A. Muhowski[1], S. Bank[1], V.A Podolskiy[2] and D. Wasserman[1]
[1]Department of Electrical and Computer Engineering, University of Texas Austin, Austin, Texas 78758, USA
[2]Department of Physics and Applied Physics, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA
dw@utexas.edu

Abstract: We demonstrate the monolithic integration of plasmonic materials with semiconductor optoelectronic devices. Leveraging highly doped semiconductors as mid-IR plasmonic materials, we show significant performance improvement for both infrared detectors and emitters.

Plasmonics, the field of optics dedicated exploiting optical modes confined to the interface between negative and positive permittivity materials, has long been proposed as a route towards subwavelength nanophotonics. At the short wavelength side of the optical spectrum, in the visible or near-IR wavelength ranges, the materials employed for plasmonic structures are typically the noble metals, whose plasma wavelengths are usually in the ultra-violet, resulting in negative permittivity across the visible and near-IR and thus enabling these materials to support plasmonic modes across these two vital wavelength ranges. At longer wavelengths, however, the extremely large, negative permittivity of the noble metals result in an optical response much closer to that of a perfect electrical conductor, precluding the sub-diffraction limited mode volumes which make noble metals so appealing at shorter wavelengths. However, at the longer wavelengths of the mid-IR, there exists the potential to use so-called 'designer' plasmonic materials, such as doped semiconductors, where the control of carrier concentration during epitaxial growth offers the opportunity to engineer single-crystal plasmonic materials with designer-controlled permittivity, and atomic-level control of layer thicknesses [[1]]. The ability to control the spectral location of the doped semiconductor plasma wavelength (where the material transitions from a lossy dielectric to a plasmonic material), allows for the epitaxial growth of plasmonic (and epsilon-near-zero (ENZ)) material for use across the mid-IR wavelength range. Many of the cutting edge mid wave infrared (MWIR) and long wave infrared (LWIR) optoelectronic materials, such as interband cascade lasers, type-II superlattices, type-II quantum dots, and superlattice LEDs all leverage the 6.1Å lattice constant family of III-V semiconductors, the same lattice constant used for the growth of doped semiconductor plasmonic materials. Thus an additional, and perhaps most intriguing, benefit of the doped semiconductor class of plasmonic materials is the potential to monolithically integrate plasmonic materials with active optoelectronic devices, all in the same epitaxial growth.

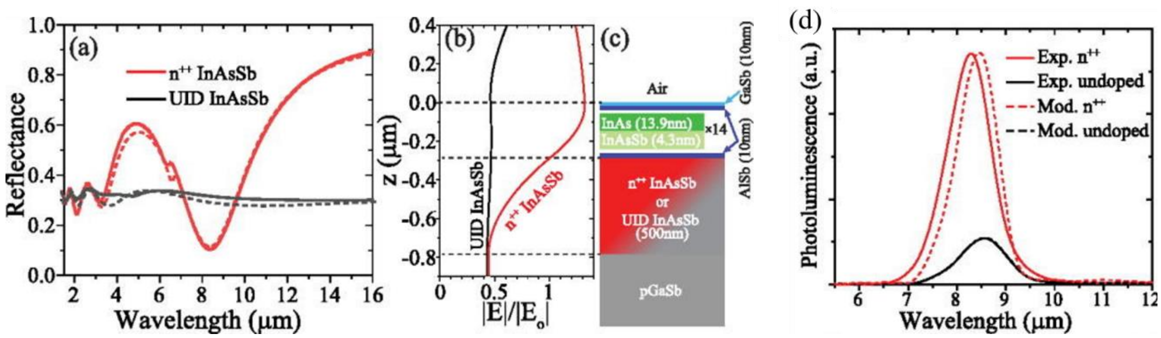

Fig. 1. (a) Experimental (solid) and modelled (dashed) reflection from the as-grown T2SL sample above a lightly doped (black) and a heavily-doped, plasmonic (red) virtual substrate. (b) Comparison of electric field profiles in the lightly doped (black) and heavily doped (red) substrate samples. (d) Sample layer stack. (d) Experimental (solid) and modelled (dashed) photoluminescence from the as-grown T2SL sample above a lightly doped (black) and a heavily-doped, plasmonic (red) virtual substrate.

Figure 1 shows the layer stack, reflection spectra, and photoluminescence spectra of two identical LWIR type-II superlattices (T2SLs) of thickness ~300nm. One of these samples is grown on an unintentionally doped virtual substrate, while the other is grown above a heavily doped semiconductor substrate. A significant improvement in photoluminescence emission intensity is observed from the sample grown on the 'designer' plasmonic substrate, a result of the strong enhancement of emission achievable for emitters placed in the near field of a plasmonic layer. The results of figure 1 serve as an example of the potential enhancement achievable in a monolithic plasmonic/optoelectronic system, and offer a strong indication as to the potential for monolithically integrated optoelectronic devices using similar architectures [2].

Figure 2(a) shows the layer stack for four different devices, each using the same T2SL LWIR absorber material. The upper stack depicts a 1.42µm thick p-i-n detector, grown above lightly doped and heavily doped virtual substrates, while the lower stack shows a 1.8µm thick p-i-n detector also grown on lightly doped and heavily doped virtual substrates. Clear LWIR absorption features are seen in the reflection spectra for the n^{++} virtual substrate samples, corresponding to a resonant cavity enhancement (RCE) of absorption enabled by the underlying plasmonic substrate, with the 1.42 µm thick device feature at ~8 µm and the 1.8 µm thick device's feature at 10 µm. Figure 2(c) shows the external quantum efficiency of all four devices as a function of wavelength, and demonstrates the clear enhancement achievable from the integration of plasmonic materials with IR active optoelectronic devices.

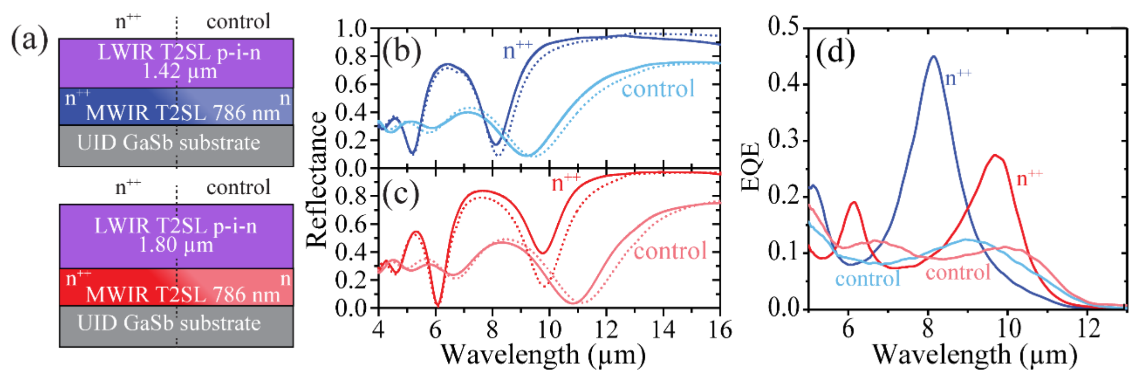

Figure 2: (a) As-grown layer stacks for the n^{++} and lightly n-doped virtual substrate devices with 1.42 µm and 1.8 µm thick detector structures above the virtual substrates. (b) Experimental (solid) and modelled (dashed) reflection spectra for the four devices shown in (a). (c) External quantum efficiency thick.

In addition, we have utilized our monolithic plasmonic/optoelectronic architecture to demonstrate enhanced efficiency mid-IR LEDs utilizing type-II nanostructures for MWIR emission, which show significant enhancement in emission, and improved temperature performance, over emitters grown on lightly doped substrates, Finally, we will present a class of ultra-thin nBn T2SL detectors operating in the LWIR with absorber regions as thin as $\lambda_o/25$, which offer a path towards ultra-low-noise LWIR detectors for high temperature operation.

In conclusion, we will present a range of devices demonstrating the first monolithic integration of plasmonic materials with semiconductor optoelectronic active regions. The presented devices offer a practical implementation for plasmonic optoelectronics at long wavelengths, and demonstrate improved performance from the current state-of-the-art in MWIR and LWIR optoelectronics. We will discuss the challenges associated with the presented architecture, and the opportunities available to develop a new class of monolithically integrated, active plasmonic devices for the infrared.

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