

Enhanced Emission from Ultra-Thin Long Wavelength Infrared Superlattices on Epitaxial Plasmonic Materials

E. Simmons¹, L. Nordin², K. Li², A. Briggs², S. Bank², D. Wasserman², and V.A. Podolskiy¹

¹Department of Physics and Applied Physics, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA

²Department of Electrical and Computer Engineering, University of Texas Austin, Austin, Texas 78758, USA

Abstract: We demonstrate an order of magnitude enhancement of emission from mid-infrared emitters monolithically integrated with semiconductor designer metals relative to the same emitters on dielectric substrates and provide theoretical explanation of the observed phenomena. © 2020 The Author(s)

The Mid- and Long-Wave IR frequency ranges rapidly emerge as the new frequency region of significant importance for pollution monitoring, healthcare, security, and materials science applications [1-4]. However, despite the significant progress in IR source technologies, the sources of IR radiation still lack in bandwidth, and efficiency as compared to their visible-range counterparts [5]. In this work, we demonstrate, experimentally and theoretically, that the monolithic integration of an ultra-thin long-wave infrared (LWIR) emitter and epitaxial designer semiconductor plasmonic metal yields an order of magnitude emission enhancement relative to the same emitter grown on a non-plasmonic material. Importantly, the plasmonic-enhanced structure demonstrates noticeable room-temperature emission when the emission from its all-dielectric counterpart is below the noise detection limit of our system.

The samples analyzed in this work are shown in Fig. 1 (a,b). Our structures are grown by molecular beam epitaxy (MBE) on a p-type GaSb substrate following the growth of a GaSb buffer. The stacks 500-nm-thick layer of either a plasmonic (n^{++}) Si:InAsSb or unintentionally doped (UID) InAsSb layer, lattice-matched to GaSb, followed by a 255 nm thick InAs/InAsSb type-II superlattice (T2SL) (14 periods), designed for an effective band-gap of 8.5 μm . The T2SL is wedged between a pair of AlSb carrier blocking layers (10 nm each), to confine carriers inside the active region. The samples are then capped with 10 nm of GaSb to prevent oxidation of the top of the AlSb layer. The emission efficiency of our samples is investigated by photoluminescence (PL) Fourier transform infrared (FTIR) spectroscopy, using amplitude modulation to eliminate background signal.

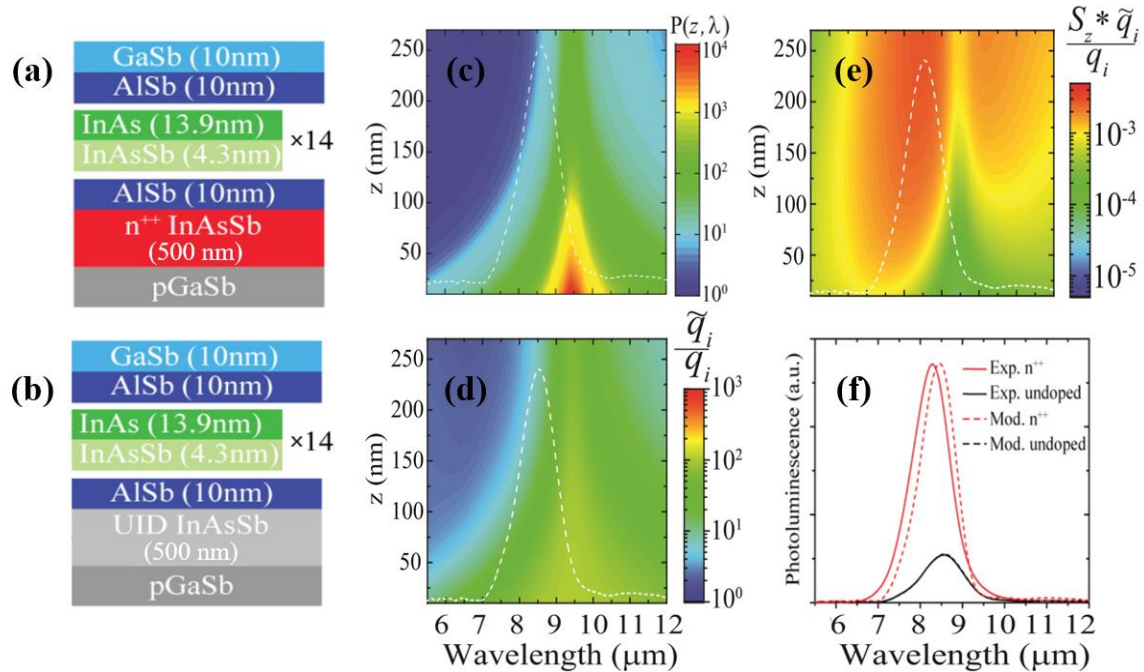


Figure 1: (a) Layered stack with n^{++} InAsSb plasmonic layer and (b) mirrored UID dielectric structure. Purcell factor (c) and intrinsic quantum yield (d) of T2SL coupled to plasmonic interface. (e) The overall predicted emission comes from the product of S_z and \tilde{q}_i . (f) The measured and predicted enhancement in emission, all plots are characterized using $q_i = 0.02$.

To understand the observed phenomenon, the process of emission is modeled numerically using a dyadic Green's function formalism [6]. In this approach, the emitters within the T2SL layers are approximated as a large

number of randomly oriented point dipoles. The field of an individual point dipole is then represented as a linear combination of the plane waves whose multiple reflections within a multilayer stack are taken into account with a transfer matrix method (TMM) [6]. Overall, the resulting numerical calculation provides both the cavity-induced radiation reaction on the dipole (Purcell factor P) and the directionality of the resulting emission (given by the \hat{z} component of the Poynting flux S_z).

The total emission detected in the far field is given by the product $S_z \tilde{q}_i$, integrated over the solid angle collected from the sample and focused onto the detector, with $\tilde{q}_i = \frac{Pq_i}{1+(P-1)q_i}$ being the modified intrinsic quantum efficiency of the T2SL emitters (q_i). Fig.1 (c-e) illustrates the dependence of the Purcell factor, the modified quantum efficiency, as well as the overall far-field emission as a function of the emission wavelength and position of the point dipole within a stack. It is seen that for the structures with relatively low intrinsic quantum yield q_i , typical of LWIR emitters, the plasmonic substrate provides significant enhancement of emission efficiency by increasing the local optical states via addition of surface plasmon polariton modes. However, the enhancement of the far-field emission represents a trade-off between enhancement of the quantum efficiency (via the Purcell effect) and the multilayer-induced reshaping of the dipole emission profile (characterized by S_z). The strong wavelength dependence of the Purcell effect yields a re-shaping of the emission spectrum, resulting in the shift of the emission maximum.

Fig.1 (f) illustrates the evolution of the spectrum, along with predicted emission enhancement for low- q_i structures. In particular, for $q_i \simeq 0.02$ (typical for mid- and LWIR T2SL emitters [7]) both spectral reshaping as well as overall emission enhancement match data observed in our experiment.

Our work, demonstrating the strong emission enhancement in monolithically integrated all semiconductor of an ultra-thin LWIR emitter and epitaxial plasmonic system, along with the developed theoretical formalism describing the observed enhancement and spectral reshaping, opens a new class of novel LWIR emitters with tailorable optical properties not previously realized.

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