Physical Modeling of Interband Tunneling & Transitions in InAs/GaSb Broken-Gap Heterostructure Lasing Devices

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BIOGRAPHY

Dwight L. Woolard: U.S. Army Research Office (ARO) - U.S. Army Research Laboratory (ARL) Program Manager for Solid-State & High-Frequency Electronics directing research thrusts in Nanometer-Scale & Molecular-Level Electronics and Terahertz-Frequency & Ultra-Fast Electronics. Dr. Woolard has been active in the research areas of THz-Frequency Biosensing Science, THz-Frequency Oscillations & Lasing in Solid-State Tunneling Devices and Novel Nanoscale/Molecular Device Concepts since joining the ARL in 1993. Dr. Woolard is a graduate of North Carolina State University; was elected to IEEE Fellow in 2004 and was the recipient of the 2008 IEEE-USA Harry Diamond Award, both for his contributions and leadership to sensing science and device technology at terahertz frequencies; and, was recognized for his Program Management by a 2011 U.S. Army SBIR Achievement Award.

TECHNICAL ABSTRACT

Since the initial growth and investigations into type II InAs/GaSb superlattices by Sai-Halasz, Tsu and Esaki [1], the 6.1 Å “lattice constant” family has received substantial attention from experts working in the infrared regime. This is motivated by the broken-gap band type alignments that enable the desired long-wavelength operation that can be tuned from the mid to far infrared through the structural design of the well-barrier layers. In addition, alloying of Al or In into GaSb can be used to adjust the amount of broken gap (i.e., to less than 0.15 eV) for further refinements to separations between conduction band (CB) and valence band (VB) energy levels. Hence, InAs/GaSb applications work on photodiodes extends to the far infrared. Radiation sources are also an area of interest, but have been limited to the infrared regime, with some examples being: a Type-II intersubband laser as described in Ref. [2], Type-II cascade lasing devices as given in Ref. [3], and, a W-shape Type-II mid-infrared laser discussed in Ref. [4].

This presentation will discuss the physics-based modeling of type II InAs/GaSb heterostructures using a Kane multiband formalism that reveals new strategies for achieving electron-injection driven lasing from the infrared to the THz regime. Here, a “prototype” laser device consisting of a double-barrier (DB) broken-gap (BG) resonant tunneling diode (I-RTD) is introduced [5]. The basic physical properties and performance advantages of this device are explained in Fig. 1. Since this heterostructure is narrow-band, the electron dynamics are dictated by multi-band interactions with multiple sets of resonant tunneling states arising in both the CB and VB. Under bias eV, electrons from the emitter tunnel through E2 and penetrate the second GaSb barrier. Simultaneously, VB electrons confined inside the second GaSb barrier are able to interband tunnel into the collector region. This processes creates a pool of confined heavy-holes (HHs) that fill statistically such their total energy is the sum of the quasi-confined HH level Ehh plus the in-plane nonlinear dispersion contribution (i.e., plotted negative relative to VB edge) creating a HH-band Ehh-to-Et. A summary of the key features are: (i) HH interband tunneling can be used to realize ultra-fast depopulation of the lower state (time constants < 1-100 ps achievable for THz operation, depending on the in-plane momentum k, as shown in Fig. 2 (left side); (ii) a large THz optical gain > 1000 cm⁻¹ can be achieved as demonstrated by results in Fig. 2 (right side); (iii) degrading nonradiative processes (e.g. AP, POP and Auger) are suppressed because electron and hole confinements are spatially-separated by the broken-gap heterostructures. The calculations indicate the AP scattering time τap is in the order of μs, and the POP mode scattering time τop is in the order of 800 ps and the Auger recombination time is on the order of ns.

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Therefore, results of physics-based modeling combined with microdisk cavity design analysis will be used to illustrate the potential output power and operational performance of this laser source concept from IR to THz frequencies in the context of expected losses and thermal heating. This new laser concept will be shown to be particularly promising at very long wavelengths. Specifically, these electron-injection driven DB-BG-RTD devices are directly amenable for integration into microdisk resonators with predicted TE polarized vertical lasing emission that should significantly exceed the existing state-of-the-art in output power performance, e.g., up to 1-10 mW from a single microdisk DB-BG-RTD in the 1-3 THz range with potential for further increases using quantum-dot nanopillar arrays.

Keywords: type II InAs/GaSb heterostructures, interband tunneling, interband transition, lasing, terahertz, infrared

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