RTD Light Emission around 1550 nm with IQE up to 6% at 300 K

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Resonant tunneling diodes (RTDs) have come *full-circle* in the past 10 years after their demonstration in the early 1990s as the fastest room-temperature semiconductor oscillator, displaying experimental results up to 712 GHz and f_{max} values exceeding 1.0 THz [1]. Now the RTD is once again the preeminent electronic oscillator above 1.0 THz and is being implemented as a coherent source [2] and a self-oscillating mixer [3], amongst other applications. This paper concerns RTD electroluminescence – an effect that has been studied very little in the past 30^+ years of RTD development, and not at room temperature. We present experiments and modeling of an *n-type* $In_{0.53}Ga_{0.47}As/AlAs$ double-barrier RTD operating as a cross-gap light emitter at ~300K. The MBE-growth stack is shown in Fig. 1(a). A 15-µm-diam-mesa device was defined by standard planar processing including a top annular ohmic contact with a 5-µm-diam pinhole in the center to couple out enough of the internal emission for accurate free-space power measurements [4]. The emission spectra have the behavior displayed in Fig. 1(b), parameterized by bias voltage (V_B). The long wavelength emission edge is at $\lambda = 1684$ nm - close to the $In_{0.53}Ga_{0.47}As$ bandgap energy of $U_g \approx 0.75$ eV at 300 K. The spectral peaks for $V_B = 2.8$ and 3.0 V both occur around $\lambda = 1550$ nm ($h\nu = 0.75$ eV), so blue-shifted relative to the peak of the "ideal", bulk InGaAs emission spectrum shown in Fig. 1(b) [5]. These results are consistent with the model displayed in Fig. 1(c), whereby the broad emission peak is attributed to the radiative recombination between electrons accumulated on the emitter side, and holes generated on the emitter side by interband tunneling with current density J_{inter}. The blue-shifted main peak is attributed to the quantum-size effect on the emitter side, which creates a radiative recombination rate $R_{N,2}$ comparable to the band-edge cross-gap rate $R_{N,1}$. Further support for this model is provided by the shorter wavelength and weaker emission peak shown in Fig. 1(b) around $\lambda = 1148$ nm. Our quantum mechanical calculations attribute this to radiative recombination $R_{R,3}$ in the RTD quantum well between the electron ground-state level $E_{1,e}$, and the hole level $E_{1,h}$.

To further test the model and estimate quantum efficiencies, we conducted optical power measurements using a large-area Ge photodiode located ≈3 mm away from the RTD pinhole, and having spectral response between 800 and 1800 nm with a peak responsivity of $\Re \approx 0.85$ A/W at $\lambda = 1550$ nm. Simultaneous I-V and L-V plots were obtained and are plotted in Fig. 2(a) with positive bias on the top contact (emitter on the bottom). The I-V curve displays a pronounced NDR region having a current peak-to-valley current ratio of 10.7 (typical for $In_{0.53}Ga_{0.47}As$ RTDs). The external quantum efficiency (EQE) was calculated from $EQE = e \cdot I_P/(\Re \cdot I_E \cdot h\nu)$ where I_P is the photodiode dc current and I_E the RTD current. The plot of EQE is shown in Fig. 2(b) where we see a very rapid rise with V_B, but a maximum value (at $V_B = 3.0$ V) of only $\approx 2\times10^{-5}$. To extract the internal quantum efficiency (IQE), we use the expression $EQE = \eta_c \cdot \eta_i \cdot \eta_r \equiv \eta_c \cdot IQE$ where η_c, η_i, and η_r are the optical-coupling, electrical-injection, and radiative recombination efficiencies, respectively [6]. Our separate optical calculations yield $\eta_c \approx 3.4\times10^{-4}$ (limited primarily by the small pinhole) from which we obtain the curve of IQE plotted in Fig. 2(b) (right-hand scale). The maximum value of IQE (again at $V_B = 3.0$ V) is 6.0%. From the implicit definition of IQE in terms of η_i and η_r given above, and the fact that the recombination efficiency in $In_{0.53}Ga_{0.47}As$ is likely limited by Auger scattering, this result for IQE suggests that η_i might be significantly high.

To estimate η_i, we have used the experimental total current of Fig. 2(a), the Kane two-band model of interband tunneling [7] computed in conjunction with a solution to Poisson's equation across the entire structure, and a rate-equation model of Auger recombination on the emitter side [6] assuming a free-electron density of 2×10^{18} cm^3. We focus on the high-bias regime above $V_B = 2.5$ V of Fig. 2(a) where most of the interband tunneling should occur in the depletion region on the collector side [$J_{inter,2}$ in Fig. 1(c)]. And because of the high-quality of the InGaAs/AlAs heterostructure (very few traps or deep levels), most of the holes should reach the emitter side by some combination of drift, diffusion, and tunneling through the valence-band double barriers (Type-I offset) between InGaAs and AlAs. The computed interband current density J_{inter} is shown in Fig. 3(a) along with the total current density J_{tot}. At the maximum J_{inter} (at V_B=3.0 V) of 7.4×10^2 A/cm^2, we get $\eta_i = J_{inter}/J_{tot} = 0.18$, which is surprisingly high considering *there is no p-type doping in the device*. When combined with the Auger-limited η_r of 0.41 and $\eta_c \approx 3.4\times10^{-4}$, we find a model value of IQE = 7.4% in good agreement with experiment. This leads to the model values for EQE plotted in Fig. 2(b) - also in good agreement with experiment.

Finally, we address the high J_{inter} and consider a possible universal nature of the light-emission mechanism. Fig. 3(b) shows the tunneling probability T according to the Kane two-band model in the three materials, $In_{0.53}Ga_{0.47}As$, GaAs, and GaN, following our observation of a similar electroluminescence mechanism in GaN/AlN RTDs (due to strong polarization field of wurtzite structures) [8]. The expression is $T_{inter} = (\pi^2/9)\cdot\exp[(-\pi^2 \cdot U_g^2 \cdot m_e)/(2h\cdot P\cdot E)]$, where U_g is the bandgap energy, P is the valence-to-conduction-band momentum matrix element, and E is the electric field. Values for the highest calculated internal E fields for the InGaAs and GaN are also shown, indicating that T_{inter} in those structures approaches values of $\sim10^{-5}$. As shown, a GaAs RTD would require an internal field of $\sim6\times10^5$ V/cm, which is rarely realized in standard GaAs RTDs, perhaps explaining why there have been few if any reports of room-temperature electroluminescence in the GaAs devices.

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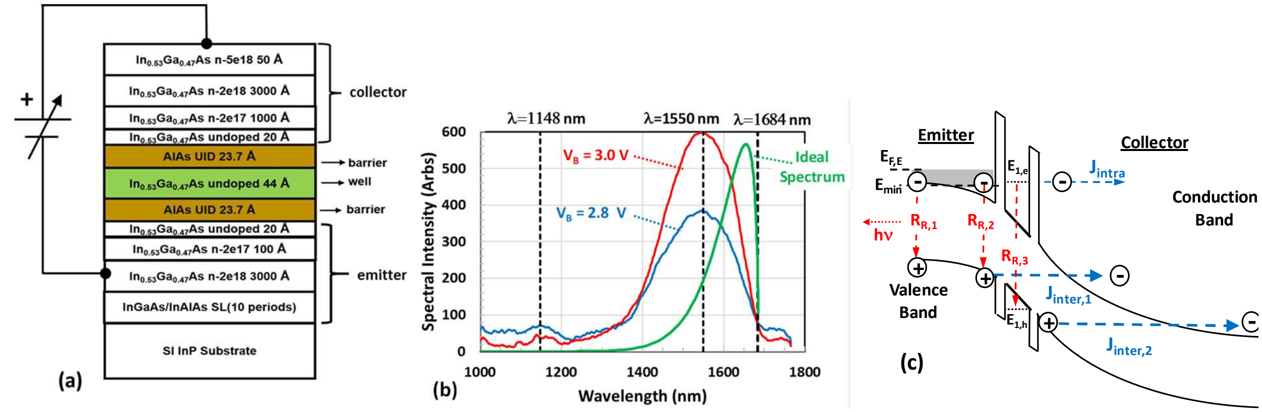

Fig. 1. (a) MBE-growth stack, (b) light emission spectra, and (c) tunneling and radiative recombination model.

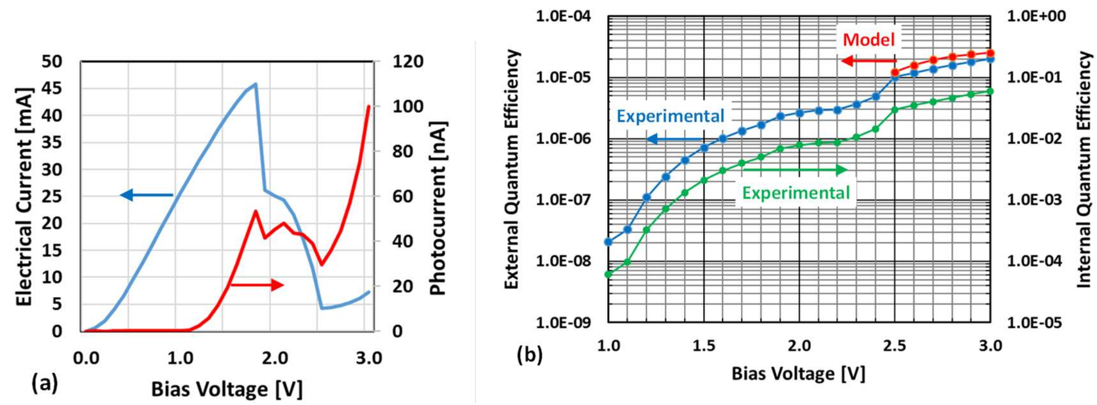

Fig. 2. (a) Experimental I-V and L-V curves, and (b) experimental and model EQE and IQE curves.

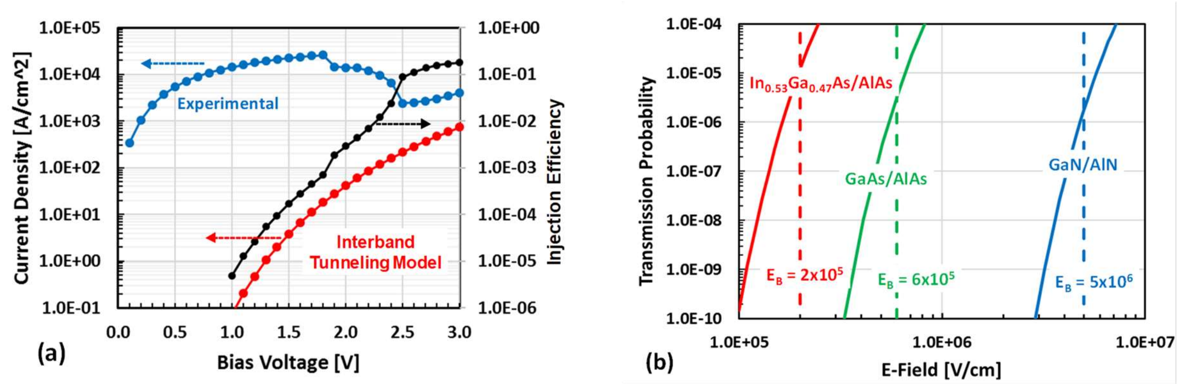

Fig. 3. (a) Experimental J-V and injection efficiency curves, and (b) tunneling probability vs E field in III-V RTDs.

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