New Device Physics of Cross-Gap Electroluminescence in Unipolar-Doped InGaAs/AlAs RTDs

P. Fakhimi[1], W-D. Zhang[2], T.A. Growden[3], E.R. Brown[2], R. Droopad[4], K.M. Hansen[2], and P. R. Berger[1]
[1]*Dept. of Electrical and Computer Engineering, Ohio State Univ., Columbus, OH 43210, USA*
[2]*Dept. of Physics, Wright State Univ., Dayton, OH 45435, USA*
[3] *NAS-NRC Postdoctoral Research Fellow at the U.S. Naval Research Laboratory, Washington, DC 20375, USA*
[4]*Ingram School of Engineering, Texas State Univ., San Marcos, TX 78666, USA*
Email: pberger@ieee.org / Phone: (614) 595-2262

Double barrier resonant tunneling diodes (DBRTDs) exhibit a characteristic negative differential resistance (NDR), which allows for high-speed oscillation and switching; e.g. $In_{0.53}Ga_{0.47}As$/AlAs DBRTDs for high-speed oscillation applications [1, 2]. Recently, a cross-gap electroluminescence (EL) phenomenon from InGaAs DBRTDs at room temperature was discovered despite the absence of p-doped layers [3]. This unipolar-doped EL had not been previously reported in the past 40^+ years of RTD history. The indispensable holes for the light emission are thought to be produced by interband tunneling through the narrow bandgap of $In_{0.53}Ga_{0.47}As$, which is illustrated in Fig. 1. The radiative recombination is thought to occur primarily in the $In_{0.53}Ga_{0.47}As$ emitter region, and thus the emission spectrum is near the bandgap of $In_{0.53}Ga_{0.47}As$ (~1650 nm at 295 K). The EL property combined with high-speed modulation can be utilized for future high-speed optical clocking applications. In this abstract we report a more detailed characterization of unipolar-doped $In_{0.53}Ga_{0.47}As$/AlAs DBRTDs to gain a better understanding of the new EL phenomenon.

The heterostructure was grown by molecular beam epitaxy (MBE) on a semi-insulating InP substrate. The heterostructure stack has a 4.4 nm thick unintentionally doped (UID) $In_{0.53}Ga_{0.47}As$ quantum well and 2.4 nm UID AlAs barriers on either side [Fig. 2 (a)]. The device shown in Fig. 2 (b) was fabricated using four mask levels. The first mask level defined a 15 µm mesa. The mesas were etched, using inductively coupled plasma reactive ion etching (ICP-RIE) with a BCl_3 gas mixture, down to the highly doped $In_{0.53}Ga_{0.47}As$ bottom contact layer in the collector region. The second mask layer was used to isolate the individual devices. A conformal passivating SiO_2 layer was then deposited using plasma enhanced chemical vapor deposition (PECVD). Contact vias were defined and etched with a CF_4 gas mixture using ICP-RIE through the SiO_2 layer with the third mask. The last mask was utilized to deposit the contact pads. The annular top (5 µm aperture) contact design allowed for more light to escape from the surface.

The characterizations entailed the following measurements: (1) current-voltage (I-V); (2) light emission intensity versus bias voltage (L-V); (3) EL spectrum; (4) shot noise; and (5) EL temperature dependence. Fig. 3 shows the measured I-V and the L-V curves at $T \approx 300$ K. The onset of NDR is at 2.2 V with a peak-to-valley ratio of ~8.3. The EL has a threshold at a lower voltage (~1.25 V). Fig. 4 shows both the full shot noise and the total RTD noise power spectral density of the $In_{0.53}Ga_{0.47}As$/AlAs DBRTD device at $T \approx 300$K. The low shot noise at biases >3V into the second positive differential resistance (PDR) region supports our thesis that the holes for the light emission are produced by interband tunneling, not impact ionization [4]. Fig. 5 shows an overlay plot of the normalized EL spectra of an RTD biased at 3.5 V with peaks marked and the theoretically modeled bandgap of $In_{0.53}Ga_{0.47}As$ at various temperatures. The consistency between the theoretical model and measured bandgap corresponding to the spectra peak further supports the theory that describes the light emission as being cross-gap, radiative recombination in the InGaAs emitter [Fig. 5, Fig. 1]. The decreasing trend in full width at half maxima (FWHM) with a decrease in temperature could be due to a reduction in phonon scattering [Fig. 6] [5]. The preliminary external quantum efficiency (EQE) measurements resulted in an EQE of ~0.44% for unipolar-doped $In_{0.53}Ga_{0.47}As$/AlAs DBRTDs. Balancing the electron resonant and interband tunneling currents via tunneling engineering can result in substantially improved EQEs.

Acknowledgements: This work was supported by the U.S. National Science Foundation (under Grants #1711733 & #1711738), Program Director, Dr. Dimitris Pavlidis.

References: [1] T. Broekaert et al, *Appl. Phys. Lett.* **53**, 1545 (1988). [2] T. Inata et al, *Japanese Journal of Applied Physics* **26**, L1332-L1334 (1987). [3] E. R. Brown et al, https://arxiv.org/abs/1804.07666. [4] E. R. Brown et al, https://arxiv.org/abs/1806.09270. [5] W. Z. Shen et al, *National Lab. of Infrared Phys.* **65**, 2728 (1994). [6] E. Zielinski et al, *J. Appl. Phys*. 59, 2196 (1986).

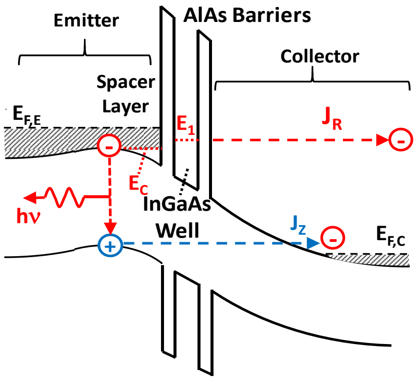
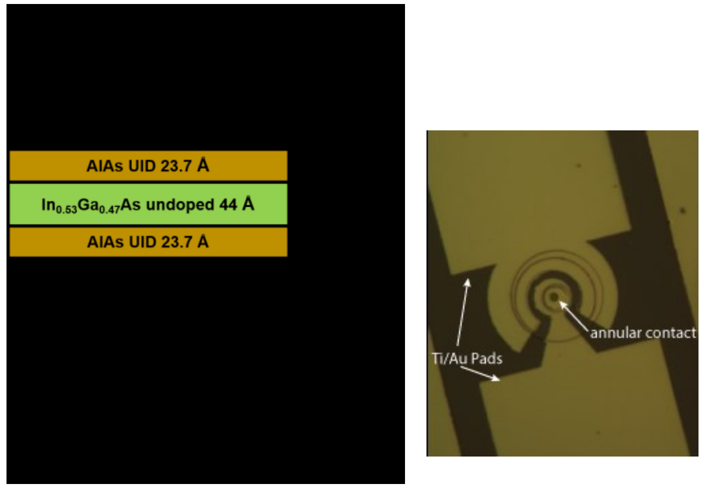


Fig. 1. The illustration of unipolar-doped light emission in InGaAs/AlAs DBRTDs.



(a) (b)

Fig. 2. (a) The heterostructure stack (b) Top-view image of the device.

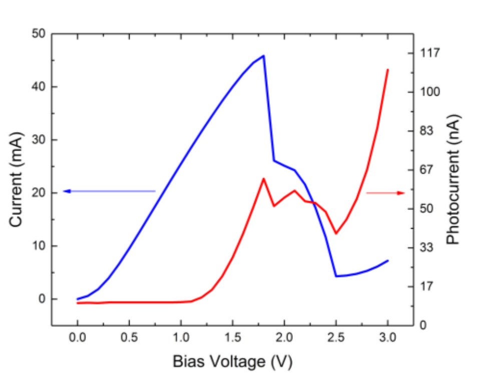


Fig. 3. I-V curve and L-V curve at T≈300 K.

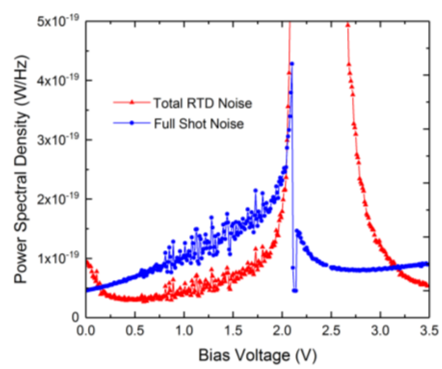


Fig. 4. Power spectral density of full shot noise and total RTD noise.

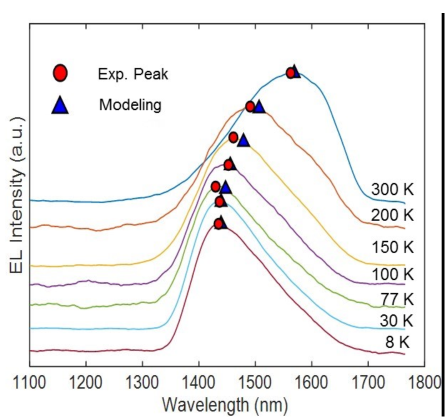


Fig. 5. (a) EL spectrum at a bias of 3.5V and theoretical modeling [6] of $In_{0.53}Ga_{0.47}As$ bandgap at different temperatures. The plots have been shifted vertically for clarity.

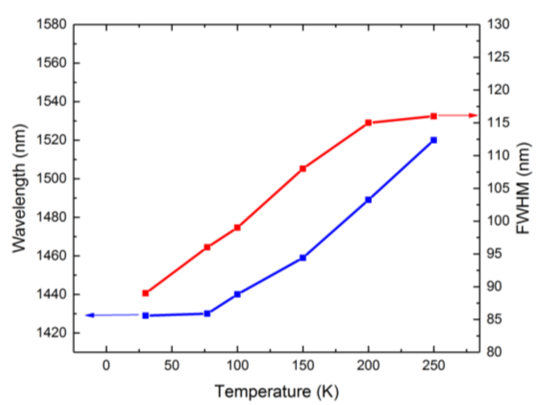


Fig. 6. Peak spectral wavelength and FWHM of EL spectra vs. temperature.