Electron-phonon scattering in THz emitters and electronics

Qing Hu, Benjamin S. Williams, Konstantinos Konistis
Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics
Massachusetts Institute of Technology, Cambridge MA 02139

M. R. Melloch
School of Electrical and Computer Engineering,
Purdue University, West Lafayette, Indiana 47907

John Reno
Sandia National Labs, 1515 Eubank Blvd SE
Albuquerque, NM 87123-0601

Terahertz (1-10 THz, or 4-40 meV, or 30-300 μm) spectrum has important application potential in remote sensing, imaging, and high-bandwidth communications. Despite the potential, however, THz frequencies are among the most underdeveloped electromagnetic spectra, primarily due to the lack of coherent solid-state sources. Semiconductor electronic devices (such as conventional transistors) are limited by the transit time to below 1 THz. On the other hand, semiconductor photonic devices (such as laser diodes) are limited to frequencies above the bandgap energy of the host materials, which is higher than 10 THz even for narrow-gap lead-salt materials.

By properly engineering subband levels and intersubband scattering rates, THz unipolar lasers may be developed based on intersubband transitions in multiple quantum well (MQW) structures. In order to achieve this goal, electrically pumped three-level systems were designed and fabricated using coupled quantum wells in GaAs/AlGaAs heterostructures. Under appropriate biases, the upper level E_3 is populated by resonant tunneling injection. The radiative transition is to take place between E_3 and E_2 levels. The ground state E_1 is designed to be $\sim\hbar\omega_{LO}$ below the E_2 level, so that fast electron-LO phonon scattering can rapidly depopulate E_2 and establish a population inversion between E_3 and E_2.

Our dc tunneling and THz emission measurements confirmed our design analysis. The emission spectra showed a peak at 2.57 THz, which is close to the designed emission frequency of 2.7 THz. The FWHM emission linewidth is as narrow as 0.5 THz, indicating a high quality of the heterostructure interface and a good uniformity of the well widths. The emission linewidth remains approximately constant up to 80-K device temperature. Careful analysis shows that several phonon-related issues are uniquely important for THz intersubband lasers, but are negligible for mid-infrared quantum-cascade lasers. These are LO-phonon scattering of hot electrons, interface and confined phonon modes, and the effect of phonon bottlenecks.

In order to push the upper frequency limit of electronic devices, we have also investigated a novel heterostructure bipolar transistor (HBT). In this transistor, the conduction band of the base is formed a staircase by using bandgap engineering. The energy of each step is slightly greater than $\hbar\omega_{LO}$. As a result, the injected minority carrier electrons will encounter very fast (~0.1 ps) inelastic scattering due to LO-phonon emission. Consequently, backward diffusion will be suppressed. Effectively, the base transient time is significantly shortened. We have performed detailed analysis on carrier transport in this novel HBT structure. Our study shows that its maximum operating frequencies can be increased from those of conventional HBTs. Furthermore, because of the phonon-enhanced forward diffusion, transit-time oscillators are feasible at frequencies far above 100 GHz.