Terahertz Emitters Based on Intersubband Transitions

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Terahertz (1−10 THz, or 4−40 meV, or 30−300 μm) frequencies are among the most underdeveloped electromagnetic spectra, even though their potential applications are promising for spectroscopy in chemistry and biology, astrophysics, plasma diagnostics, remote atmospheric sensing and imaging, noninvasive inspection of semiconductor wafers, and communications. This underdevelopment is primarily due to the lack of coherent solid-state THz CW sources that can provide high radiation intensities (greater than a milliwatt). The THz frequency falls between two other frequency ranges in which conventional semiconductor devices have been well developed. One is the microwave and millimeter-wave frequency range, and the other is the near-infrared and optical frequency range. Semiconductor electronic devices that utilize the transport of free charge carriers (such as transistors, Gunn oscillators, Schottky-diode frequency multipliers, and photomixers) are limited by the transit time and parasitic RC time constants. Consequently, the power level of these classical devices decreases as $1/f^4$, or even faster, as the frequency f increases above 1 THz. Semiconductor photonic devices based on quantum-mechanical interband transitions, however, are limited to frequencies higher than those corresponding to the semiconductor energy gap, which is higher than 10 THz even for narrow-gap lead-salt materials. Thus, the frequency range of 1−10 THz is inaccessible for conventional semiconductor devices.

Semiconductor quantum wells are human-made quantum-mechanical systems in which the energy levels can be designed and engineered to be of any value. Consequently, unipolar lasers based on intersubband transitions (electrons that make lasing transitions between subband levels) were proposed for long-wavelength sources as early as the 1970s, and have been realized in quantum-cascade lasers (QCLs) at infrared frequencies. Inspired by this great success, we have investigated THz emitters based on intersubband transitions with the ultimate goal to develop THz lasers. In this presentation, we will discuss two types of electrically pumped intersubband THz emitters. One utilizes electron-LO-phonon scattering, and the other utilizes resonant tunneling to depopulate the lower radiative level in order to achieve population inversion.

The design principle of the first structure is similar to the that of the original QCLs, namely it contains three subband energy levels E_3, E_2, and E_1, with the energy separation between E_2 and E_1 slightly greater than the LO-phonon energy $\hbar\omega_{LO}$. Since it is energetically allowed, the fast electron-LO-phonon $E_2 \rightarrow E_1$ scattering will help to keep the population in E_2 low, and therefore maintain a population inversion between E_3 and E_2. Under appropriate biases, one structure emits THz radiation as a result of diagonal (or interwell) intersubband transition. 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.

In the second type of structure that we have investigated, the radiative transition is vertical spatially (or intrawell). This structure tends to yield large radiative dipole moments and narrow linewidths because of a strong spatial overlap between the two radiative levels. As expected, the measured emission spectra showed a peak with an narrower (0.18 THz) linewidth at the designed frequency of 5 THz. However, because $E_3\text{-}E_2 < \hbar\omega_{LO}$, it is difficult to design this structure that utilizes electron-LO-phonon scattering for depopulation. Instead, the depopulation of E_2 is facilitated through "resonant tunneling" from E_2 to E_1. In order to identify whether the tunneling between E_2 to E_1 is incoherent between two spatially localized states (which is slow), or coherent between two spatially overlapped ones (which is fast), we have performed magnetotunneling spectroscopy on these emitter structures. The magnetoconductance oscillation clearly reveals the existence of an anticrossing gap of ~2 meV, indicating a coherent coupling between E_2 and E_1.