Numerical simulation of extraction barrier width effects on terahertz quantum cascade laser

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***Abstract*—The effect of extraction barrier width on a resonant-phonon terahertz quantum cascade laser is studied using the Monte Carlo method. The width of extraction barrier is varied from 48 to 33 Å. The calculated threshold current density increases monotonously with decreasing extraction barrier width, while the peak gain shows nontrivial behavior. The simulation results suggest an optimum extraction barrier width of 36 Å for peak gain.**

I. Introduction And Background

Quantum cascade laser (QCL) working in the far-infrared or terahertz (THz) range was first realized in 2001. Tremendous improvements have been made to its performance since then. It plays a key role in many THz applications, such as imaging and sensing. Further performance improvement will lead to wider applications. So the pursue of higher output power, higher working temperature, and wider lasing frequency never stops.

Recently, a series of experiments designed for searching the optimum values of resonant-phonon THz QCLs has been carried out and suggests that the doping concentration, injection and extraction barrier width are three parameters which expected to have a major impact on the device performance. The optimum doping concentration and injection barrier width are identified for the THz QCLs based on resonant-phonon design, but no optimum extraction barrier width was found for maximum lasing temperature. Theoretical simulation has its advantage in this case, since there is no limitation on the parameters used. In this letter, we use the ensemble Monte Carlo (MC) method to study the effect of extraction barrier width on the performance of a resonant-phonon THz QCL. The simulation results agree well with the experimental measurements. We find an optimum extraction barrier width of 36 Å for peak gain, which is not accessible to the experiment.

II. Results

The main focus of our simulation is a series of GaAs/$Al_{0.15}Ga_{0.85}As$ QCLs based on resonant-phonon three-well design. We only include electron-electron (e-e) and electron-phonon (e-p) scatterings in our MC model to release the burden of the long computing time. A typical band structure together with the squared wave functions of the most important states are shown in Fig. 1(a). Starting from the injection barrier, the layer thicknesses in Å are **48**/96/**20**/74/**42**/161, where the $Al_{0.15}Ga_{0.85}As$ barriers are in boldface and GaAs wells in plain text. The 161 Å injection well is doped at 3.6×10^{10} cm^{-2} in the center. To study the effect of extraction barrier width, we change it from 48 to 33 Å with a stepsize of -3 Å.

Calculated peak gain and threshold current density for different extraction barrier widths are shown in Fig. 1(b). With decreasing extraction barrier width, the peak gain has a maximum 110 cm^{-1} at 36 Å. Threshold current density increases monotonously from 436 to 1054 A/cm^2 with the extraction barrier width changing from 48 to 33 Å. To take a further quantitative analysis on the increasing (threshold) current density with decreasing extraction barrier width, we investigate the electron relaxation time from level 3 to 2 (τ_{32}). We find that τ_{32} decreases from 24.0 to 7.8 ps with decreasing extraction barrier width from 48 to 33 Å. The decreasing relaxation time indicates an enhancement of extraction efficiency with the reduction of extraction barrier width and results in increasing (threshold) current density. Because the population inversion ΔN_{43} is also related with the electron injection efficiency from level 1' to 4 and nonradiative relaxation time τ_{34}, we don't observe obvious changes in population inversion though the τ_{32} has a big change with decreasing extraction barrier width.

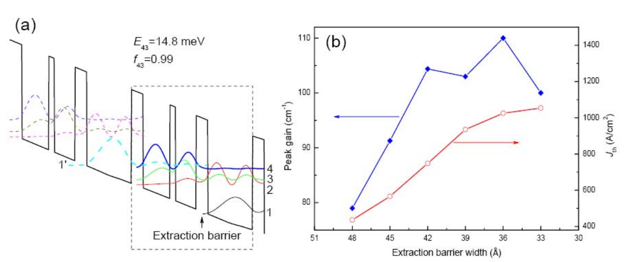

Fig. 1: (a) Calculated band structure under the design bias of 14.4 kV/cm. (b) Peak gain (left) and threshold current density J_{th} (right) as a function of extraction barrier width.

References

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