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Electrically Confined Quantum Dot Intersubband Optoelectronic Devices

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Intersubband optoelectronic devices such as mid-infrared lasers and photodetectors that utilize the intersubband energy spacing (3-20 μm) are in great need for applications such as space based infrared imaging, thermal imaging, FTIR spectroscopy, and environmental and chemical process monitoring. However, the conventional quantum well (QW) based intersubband devices still have some fundamental limitations due to the continuous electronic spectrum in QWs. For example, Quantum Well Cascade lasers (QCLs) still face the limitations of fast depletion of the upper laser level by non-radiative LO-phonon-assisted emission as well as high optical loss[1], and Quantum Well Infrared Photodetectors (QWIPs) still require to work at a low temperature owing to high thermionic emission rates and they cannot detect normal incidence radiation due to polarization selection rules[2]. These limitations can be avoided in principle by applying quantum dots (QDs) into these intersubband devices since the 3-D confinements in QDs. The idea of using QDs into cascade lasers and infrared photodetectors have been widely studied and confirmed[3]. Different techniques such as self-assembly growth[4], electron-beam lithography[5], and applying magnetic field[6] have been proposed to fabricate QDs. Here we will present a novel method of forming QD based on the lateral confinement on QW by electrical field as show in figure 1. The electrical field would deplete the QW into a very small region, forming a "quantum disk". The field induced lateral confinement combined with the vertical confinement of the QW would form a three dimensional confinement. A similar idea of using a lateral electrical field to deplete and form a quantum ring has been proposed by Lorens et al[7]. To use this idea to make QD intersubband devices, we have designed a novel device structure as shown in figure 2(a), which can be both used for cascade lasers and intersubband photodetectors. In this structure, gate contact, insulator below the gate, and semiconductor substrate form a metal-insulator-semiconductor (MIS), and the gate forms a depletion region in the semiconductor area nearby. Therefore most electrons are confined in the nano-channel below the nano-injector contact, as shown in figure 2(b). In this nano-channel, the lateral energy confinement breaks the in-plane periodic lattice potential and collapses the energy bands into energy states just like QDs. With different gate voltages being applied, it will form different depletion widths in the QWs and thus effectively changes the size of the QDs. As shown in figure 3, using 3-D finite-element-method simulations we found that the electron energies were shifted to higher values with a more negative gate voltages applied and the quantum states were splitted by a large value that approaches ~2kT at room temperature. The typical electron state wave functions are also shown in figure 3. To further develop the idea and put it into functional devices, design and fabrication of the intersubband cascade laser and photodetector devices are undergoing. Figure 4 shows typical Scanning Electron Microscope (SEM) cross-sectional images of QD devices we have fabricated. Work is still undergoing to finalize and characterize the devices.

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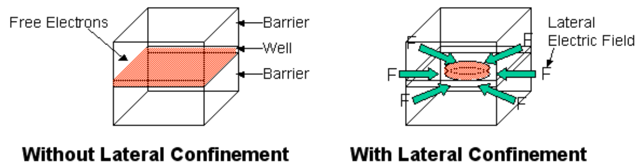

Figure 1. Schematic picture of a single quantum well without (left) and with (right) lateral electrical field

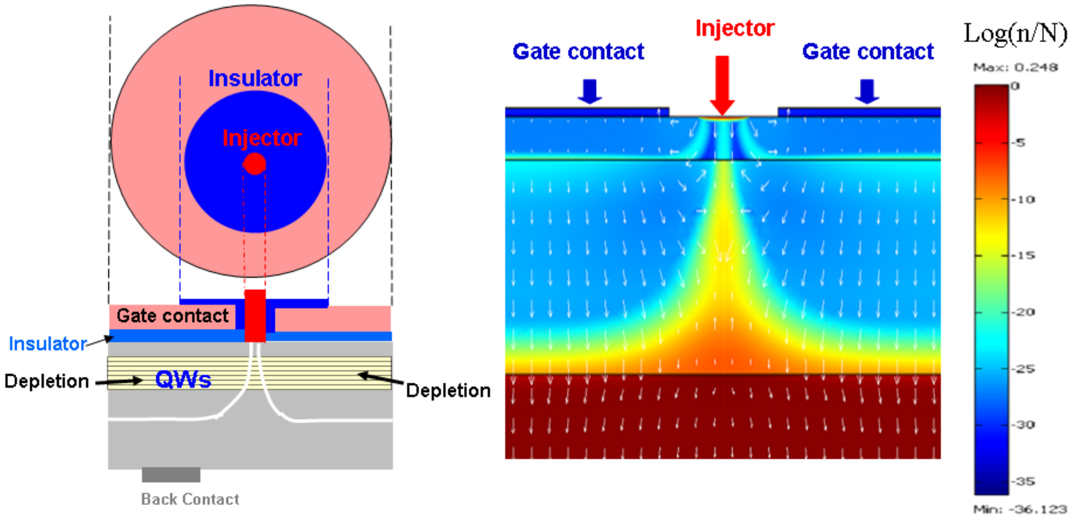

Figure 2 (Left) Schematic picture of our novel intersubband device structure (the white dash lines are the iso-potential lines, the electrons are depleted into the nano-channel below the injector); (right) a 2D FEM (finite-element-method) simulation shows most electrons are depleted into the nano-channel below the injector (red color means the highest electron concentration, the value is log[n/N], where n is the electron concentration and N is the doping concentration of the semiconductor).

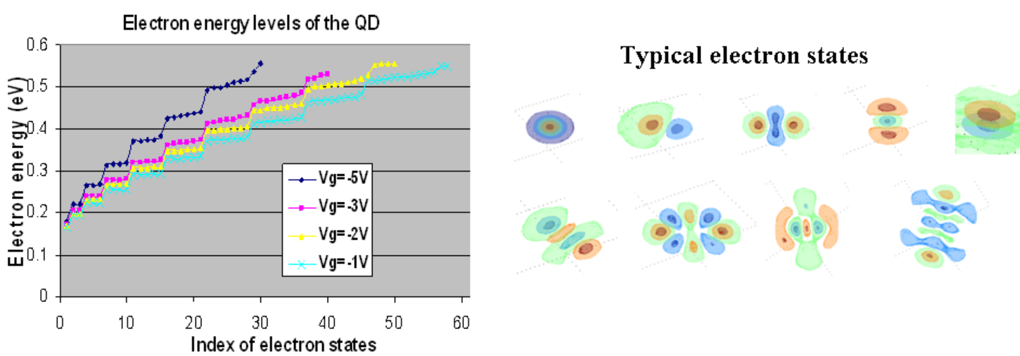

Figure 3 (Left) Electron energy level of a single quantum well after lateral electron confinement with different gate voltages, the energy band has splitted into different energy states; (right) typical electron wavefunctions for different energy levels representing s, p, d, and f-like states.

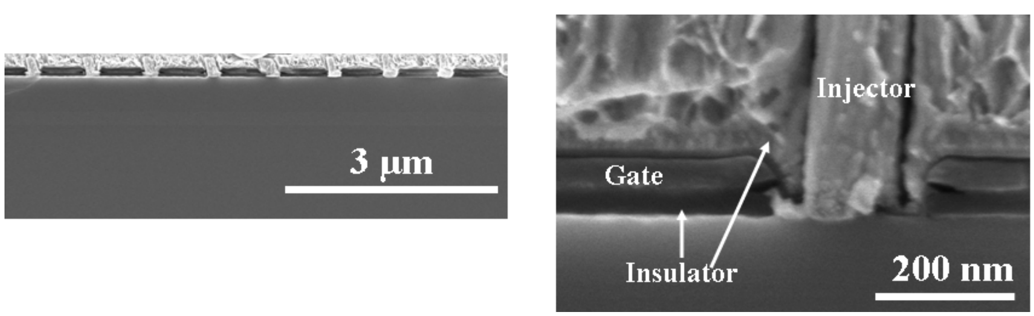

Figure 4 (Left) SEM cross-sectional images of series of QD structures, and (right) enlarged view of a QD device