Interlevel Cascade Transition in Electrically Confined Quantum Wire Arrays

Wei Wu, Iman Hassani, and Hooman Mohseni*

Bio-inspired Sensors and Optoelectronics Laboratory (BISOL), Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208, United States

Quantum structures such as quantum dots (QDs) or wires (QWRs) have unique electronic and optical properties because of their multidimensional quantum confinement. For example, strongly nonlinear transport characteristics, such as Coulomb blockade and resonant tunneling, have been demonstrated in the low-dimensional structures. A decrease of the nonradiative losses due to the reduced electron-longitudinal-optical-phonon (LO-phonon) scattering has also been shown in the quantum structures. Because of their unique properties, quantum structures are very attractive for optoelectronic device applications. The transport and photonic phenomena studies of quantum structures have resulted in the development of tunneling injection quantum dot lasers and quantum wire intersubband emitters and photodetectors. Recently, the interlevel/intersublevel cascade transitions of carriers have also been studied and developed for terahertz quantum cascade laser applications. Most experimental realizations of the quantum structures rely on physical material removal (etching), which produces inevitable structural damage and device performance degradation. Other methods, such as self-assembled growth, have addressed this issue but result in limited size uniformity over large areas. Electrical confinement methods, such as using multiple top metal gates to deplete the two-dimensional electron gas in a heterostructure, have been widely used to form low-dimensional structures. However, the geometry of these ultrathin devices renders extremely small overlap to optical modes within the visible/infrared bands, and hence they have been mainly used for lateral transport studies and electronic devices. Forming vertical stacks of uniform quantum structures is an attractive method to increase the interaction between photons and electrons.

Nonetheless, electronic vertical transport and carrier transitions in stacked QWRs are much less studied compared with its potential applications. For example, the resonant tunneling and the reduced nonradiative losses in quantum wires could lead to development of novel terahertz emitters and detectors working at high temperatures.

Here we report on a novel method of forming vertical stacks of QWRs based on an external electric field confinement of carriers in quantum wells and experimentally study the transport property of the structure at different temperatures. Using a distributed metal gate, we induce electrical depletion in the quantum wells around a nanoridge of 200 nm width. This produces a strong lateral confinement, in addition to the vertical confinement produced by the heterojunctions, to create tunable QWRs. The schematic of the proposed device structure is shown in Figure 1. The long nanoridge arrays of highly doped In0.53Ga0.47As are used to connect the top contacts of all quantum wires and to produce an undercut in the lower layer of InP, which can help disconnect the gate from the top contacts. With a negative gate voltage, the generated electric field can effectively deplete the electrons from the areas below the nanoridges.

* Address correspondence to hmohseni@northwestern.edu.

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and form quantum confinement in the lateral direction. On the basis of this idea, we successfully realize the QWR devices experimentally and present the electrical and optical verification of this lateral confinement. Multiple current plateaus and strong differential conduction oscillations up to 123 K were observed. Our modeling shows that resonant tunneling between the energy states in different quantum wells produced by electrical confinement is responsible for this behavior. Also, the model predicts the measured red-shift of the peak photoresponse accurately.

**DEVICE FABRICATION**

The quantum well structure was grown by metal-organic chemical vapor deposition (MOCVD) on a semi-insulation (100) InP substrate. The active region, sandwiched between 500 nm n-doped In₀.₅₃Ga₀.₄₇As (doping concentration 10¹⁸ cm⁻³) at the bottom and 40 nm at the top, consists of 8 periods of 50 nm InP barriers and 5.6 nm n-doped In₀.₅₃Ga₀.₄₇As wells with a nominal doping concentration of 2.5 × 10¹⁷ cm⁻³. The thickness of the first InP barrier from the top is 100 nm and is used for formation of the undercut. Because of the good adhesion between epitaxial layers of In₀.₅₃Ga₀.₄₇As and InP, In₀.₅₃Ga₀.₄₇As nanoridges were used as masks to wet etch the InP layer below and form the undercut shape along the (01T) direction. A thin dielectric layer of SiO₂ was deposited before the deposition of the gate layer. The periodic highly doped In₀.₅₃Ga₀.₄₇As nanoridge arrays of 200 nm width and 1 μm periodicity were formed by electron beam lithography and subsequent reactive ion etching (RIE) of In₀.₅₃Ga₀.₄₇As. Within a device, all nanoridges were connected at one end, and all the gate contacts were connected at the other end.

Figure 2 shows the major fabrication sequence for the electrically confined QWR device. First, a HSQ e-beam resist was patterned on top of the quantum wells sample by electron beam lithography to form periodic nanoridge arrays, and the nanoridges were used as masks to transfer the patterns to the In₀.₅₃Ga₀.₄₇As layer (Figure 2a). Second, a SiO₂ layer was deposited using plasma-enhanced chemical vapor deposition (PECVD) and patterned so that it was used as a mask to etch the whole QW active layer until reaching the bottom doped In₀.₅₃Ga₀.₄₇As contact layer
and form separate mesas including the active layers (Figure 2b). Third, a thick Si$_x$N$_y$ layer was deposited by PECVD and patterned to make an opening on top of the mesas (Figure 2c), and the first InP layer of 100 nm was etched using hydrochloric acid (HCl) and phosphoric acid (H$_3$PO$_4$) mixed solutions at 0 °C. The mixed solution almost does not attack the In$_{0.53}$Ga$_{0.47}$As layer. Because the In$_{0.53}$Ga$_{0.47}$As nanoridges form along the $\langle 01\bar{T}\rangle$ direction on the (100) InP wafer, the wet etching of InP formed a strong undercut shape. Figure 2d shows the side view normal to the nanoridges. Fourthly, a thin layer of SiO$_2$ was deposited using PECVD as gate dielectric, and a thin layer of Ti and Au was deposited and patterned to form the gate contacts (Figure 2e). Because of the strong undercut and thin SiO$_2$ layer, the gate and top metal contact layers were electrically disconnected (Figure 2f). Lastly, a thick Ti/Au metal layer was deposited and patterned to generate the top, gate, and ground contacts (Figure 2h).

**RESULTS AND DISCUSSION**

The transport property of the device was measured in a temperature-controlled optical cryostat cooled with liquid nitrogen. Figure 4 shows the typical dark current curves at different temperatures. Multiple current plateaus are observed when the bias increases from 78 K up to 123 K. Above 123 K, these oscillations were masked by the large thermionic dark current. In the same figure, we also plotted the differential conductance curves of the device for the first three temperatures. A few strong conductance oscillation peaks have been observed. These oscillation peaks appear in a quasi-periodic fashion, and the peak-to-valley ratios are almost an order high. The voltage separations between the adjacent peaks are between $\sim 0.4$ and $\sim 0.9$ V, which are much larger than the conduction band offset of In$_{0.53}$Ga$_{0.47}$As and InP QWs ($\sim 0.242$ eV). Therefore, sequential tunneling$^{30}$ between the ground and bound states could not be responsible. Besides, the thickness of our quantum barriers is 50 nm, too thick for sequential tunneling (for example, barriers are $\sim 12$ nm in ref 30). We believe these strong conductance oscillations originate from the resonant tunneling of the electrons through the energy states in all quantum wells produced by the lateral confinement. To confirm this, we simulated the dark current for the electrical confined quantum wells.

In our model, we consider the dark current consisted of two parts, the thermionic and resonant tunneling current.$^{31}$ The calculations of both currents are shown.
The experimental and simulated dark current and differential conductance curves at 78 K. The average potential drop per period, $V$, is the energy of the $i$th sublevel, $E_i$ is the energy of the $i$th excited states due to the lateral electric field leads to almost equal separations between the energy levels. Considering the electrons' lifetime scattering, broadening of each energy state for quantum wires, and inhomogeneous broadening due to the nonuniformity of the electrical confinement at different depths, a broad resonant tunneling current is expected for each peak. If we add the resonant tunneling current with the thermionic one, multiple current steps and conductance oscillations appear. Figure 5b shows the simulated curve compared with the experimental one. The resonant tunneling coefficients and broadening width were fitted in the formulas above since there were no such experimental values.

The optical spectra of the device were also measured, and Figure 6a shows the normal-incident photocurrent response from the back side of the wafer at the bias of 1.25 V at 78 K for different gate voltages of 0, –1.5, and –3 V. With a more negative gate voltage, the peak responses get smaller and they shift to a longer wavelength (red-shift). This is because the photocurrent is primarily from optical excitation of electrons from lower to quasi-bond upper states in the well. With a stronger lateral electrical confinement, the energy of the lower states increases and the difference between the lower and upper states is reduced, which produces a net red-shift in the photoresponse. In parallel, the increased depletion of the lower states leads to a reduced photocurrent. To confirm this, we used a finite-element method approach to model the potential distribution through the device and then numerically calculated the quantized energy levels in the nanowires. We then calculated the transfer matrix elements and the absorption spectra for the quantum wires as a function of the gate voltages. Figure 6b shows this simulation for three gate voltages of (i), (ii), and (iii). The near-parabolic potential induced by the lateral electric field produces a plasmonic effect and induces the electric field component in the quantum well growth direction was generated from the normal incident infrared light because the nonuniform gate metal surface produces a plasmonic effect and induces the electric field component. Figure 6c shows the radial electrical potentials in the middle of the quantum wells at different gate voltages, and Figure 6d shows the simulated typical wave functions of the QWRs. The spacing between the ground and the first excited states due to the lateral electrical confinement is about 16 meV at a gate voltage of –3 V, which is significantly larger than the thermal energy at liquid nitrogen temperature ($kT \approx 6.7$ meV). Achieving a similar confinement...
using size-induced methods (e.g., etching and regrowth) requires the lateral dimension of the quantum structures to be as small as ~30 nm.\textsuperscript{34,35}

**CONCLUSIONS**

We report the fabrication and characterizations of novel electrically confined quantum wire stacks over large areas. Multiple current plateaus and conduction oscillations at above liquid nitrogen temperatures were observed due to the electrical confinement. The gate effect on the photoresponse of the detector was measured and compared with the theoretical prediction. This study demonstrates that strong lateral confinement could be utilized to produce stacks of nanowires, and potentially quantum dots, for optoelectronics applications.

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**REFERENCES AND NOTES**