Negative differential resistance effects of trench-type InGaAs quantum-wire field-effect transistors with 50-nm gate-length

Kee-Youn Jang
Japan Society for the Promotion of Science (JSPS)-Domestic Research Fellow, National Institute of Advanced Industrial Science and Technology (AIST) and CREST, Japan Science and Technology (JST), 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan

Takeyoshi Sugaya, a) Cheol-Koo Hahn, Mutsuo Ogura, and Kazuhiro Komori
National Institute of Advanced Industrial Science and Technology (AIST) and CREST, Japan Science and Technology (JST), 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan

Akito Shinoda and Kenji Yonei
Shibaura Institute of Technology, 3-9-14, Shibaura, Minato-ku, Tokyo 108-8548, Japan

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The effects of negative differential resistance (NDR) have been clearly observed in 50-nm-gate InGaAs/InAlAs trench-type quantum-wire (QWR) field-effect transistors (FETs), which are fabricated by atomic hydrogen-assisted molecular-beam epitaxy. The NDR onset voltage is as low as 0.1 V, and the highest peak-to-valley current ratio is 6.2 at 40 K. The equilateral symmetry of the NDR effect in a QWR FET is also observed. The pronounced NDR effects in a trench-type QWR FET are advantageous for high-speed and low power-consumption devices. © 2003 American Institute of Physics. [DOI: 10.1063/1.1595150]

It has been predicted theoretically that suppressed electron scattering will enhance the carrier mobility in a one-dimensional (1D) electronic system. However, in reality, the size fluctuations and irregularities found in a 1D electric channel cause more severe electron scattering and blocking than in a two-dimensional (2D) system. Therefore, the fabrication of high-quality quantum wire (QWR) is a prerequisite for 1D device applications before the theoretical prediction can be verified. The fabrication of a high-quality 1D system has commonly involved the selective growth of V-shaped and ridge-type QWR on (100) nonplanar substrates using molecular-beam epitaxy (MBE). We have fabricated an excellent trench-type InGaAs/InAlAs QWR, which we grew on an InP(311)A V-groove substrate by atomic-hydrogen-assisted MBE (H-MBE), and we observed a negative differential resistance (NDR) effect in a 2-μm-gate trench-type QWR field-effect transistor (FET). NDR effects are important in terms of their possible applications to microwave, switching, and memory devices. A low onset voltage (VNDR) and a high peak-to-valley current ratio (PVR) are important factors with respect to reducing the power consumption and improving the efficiency of such applications. A short gate length is another effective way to suppress scattering and reduce the VNDR.

In this work, we realized an extremely low VNDR of 0.1 V and a high PVR of 6.2 in a 50-nm-gate trench-type QWR FET at 40 K. We also observed clear symmetrical NDR effects at positive and negative drain voltages (from −1 to 1 V).

Figure 1 shows a cross-sectional diagram and a cross-sectional transmission electron microscope (TEM) image of the trench-type structure of InGaAs/InAlAs QWR layers grown on a (311)A InP V-groove substrate. The V-grooves were fabricated along the [01-1] direction on a (311)A InP substrate by using conventional photolithography and chemical wet etching in HCl:H3PO4:H2O2 (50:10:1). The InAlAs buffer layer was grown under As2 flux to suppress the surface migration of group-III elements. The trench structure was formed between (111)A and (331)B facets (angle of 22°), which consisted of the oblique slopes of two trap-ezoids, grown selectively on the (100) and (011) facets of the V-groove substrate. Next, a very narrow (10×25 nm) InGaAs QWR layer was grown under As2 flux in order to enhance the migration of group-III elements at the bottom of the InAlAs trench structure.

We also confirmed that the trench-type QWRs had uniform cathodoluminescence along the QWR peak at 1340 nm (0.925 eV). The natural super-

![Cross-sectional diagram of trench-type InGaAs/InAlAs QWR layer growth.](image-url)
lattices, which form in the sidewalls of the InAlAs trench structure, are effective in improving the interface and suppressing the scattering of electrons in the narrow QWR.

Figure 2 shows (a) a schematic cross-section and (b) the detailed structure of the electrode of a 50-nm gate trench-type InGaAs QWR-FET. The heterostructures for the InGaAs/InAlAs QWRs were grown by H-MBE on (311)A InP V-groove substrate at 510 °C. The epitaxial layer consists of a 400-nm InAlAs buffer layer, a 10-nm InGaAs QWR layer, an InAlAs space layer, a Schottky layer and a nonalloyed ohmic layer. A series of δ-doped layers are inserted between the 10-nm InAlAs space layer and the 15-nm InAlAs Schottky layer. The nonalloyed ohmic contact layer consists of a 1-nm n⁺-InAlAs layer, a 5-nm n⁺-InGaAs layer, a 1-nm n⁺-InAlAs layer, and a 1-nm n⁺-InAs layer.

Atomic hydrogen irradiation was performed during the layer growth in H-MBE, and was also used to clean the InP(311)A substrate surface prior to growth. This atomic hydrogen was supplied by a cracking cell, which was heated with a tungsten filament to about 1700 °C. A single QWR was isolated by selective etching in order to prevent electrons from flowing through the top quantum well (QW). A 100-nm-thick SiO₂ film was deposited for surface passivation. After the SiO₂ layer had been partially removed by photolithography and wet etching, Ti/Au metals were deposited as nonalloyed ohmic contacts by the lift-off technique. As the final processing step, a 50-nm Ti/Pt/Au Schottky gate was formed by electron-beam lithography (JBX-6000SA), using recess etching and lift-off.

Figure 3 shows the I_D–V_DS characteristics of the 50-nm gate trench-type InGaAs QWR-FET at 40 K. The onset of the NDR effects is clearly observed at a drain–source voltage as low as 0.1 V with increasing gate voltage (V_G). The measured maximum PVR for the QWR FET was 6.2 at V_G = 4 V. Such a low onset voltage (V_NDR) and large PVR have not been reported for previous NDR devices. The V_NDR should decrease with increasing gate voltage, as observed in our previous study, because the electron density of the channel increases. We observed a very slight reduction in V_NDR (the broken line in Fig. 3) with increasing gate voltage in our device, which we attribute to the reduced scattering probability with a short gate.

We also observed symmetric NDR characteristics with a trench-type QWR-FET. The inset in Fig. 3 shows the I–V characteristics of a trench-type InGaAs QWR-FET as a function of drain voltage from −1 to 1 V at 40 K. The equilateral symmetry of the NDR characteristics can be clearly seen in the V_NDR of ±0.1 V at a gate voltage of 0 V both at positive and negative drain voltages. The symmetric NDR effects indicate that there is superior interface uniformity along the InGaAs QWR.

There are three possible mechanisms for the NDR effects. One is the Gunn effect, which is explained by the intervalley transition of the electrons. The energy separation, ΔE_{TL}, between the Γ-valley and the lowest satellite valley (L-valley) of In_{0.53}Ga_{0.47}As, is about 0.55 eV; namely, larger than the V_NDR of our device. Therefore, the observed NDR cannot be explained by the Gunn effect.

The second possible mechanism is a real space transfer (RST), whereby electrons are transferred from the InGaAs QWR layer to the InAlAs space layer beneath the Schottky gate. The conduction band offset between the InGaAs QWR and the InAlAs space layer is 0.46 eV. The fundamental subband level in the trench-type QWR is located at 0.122 eV above the InGaAs conduction band. Therefore, channel electrons have to obtain at least 0.338 eV before they can escape into the InAlAs space layer. The effective band offset may be lowered by the existence of a gate electric field and an adjacent δ-doped layer; nevertheless, a V_NDR of 0.1 V is too small for this mechanism. With respect to the NDR effects of the ridge-type QWR FETs, the V_NDR was about 0.3 V and the gate leakage current was detected after the NDR had been observed. In contrast, the gate leakage current of the trench-type QWR FET was undetectable around the onset voltage of 0.1 V, as shown by the dotted curve in Fig. 3. Therefore, the V_NDR of 0.1 V cannot be explained by an
overflow of electrons from the InGaAs QWR layer into the InAlAs space layer.

The third mechanism, of which we are confident, is the transition of electrons from the high-mobility lower subband levels to the low-mobility higher subband levels with large densities of states, and this is favorable in terms of realizing a pronounced NDR effect.

In summary, we observed clear NDR effects with a $V_{\text{NDR}}$ of 0.1 V and a PVR of 6.2 in a 50-nm-gate-length, trench-type InGaAs/InAlAs QWR FET at 40 K, in a simple three-terminal configuration, in which the NDR can be controlled with the gate voltage. In addition, we clearly observed symmetrical NDR characteristics as a function of the positive and negative voltages. The NDR is explained by the intersubband transition of 1D electron states, in which carriers are transferred from the fundamental level of the QWR layer to the higher subband energy levels predominantly in the side QWs above the onset voltage of the NDR effects. A trench-type QWR FET with such clear NDR effects has great potential for use in high-speed and low-power consumption devices.

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