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InGaAs nanowire/Ge heterojunction Esaki tunnel diodes

Akinobu Yoshida, Katsuhiro Tomioka* and Junichi Motohisa

Graduate School of Information Science and Technology,
and Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University
Kita 14, Nishi 9, Sapporo 060-0814, Japan
Phone: +81-11-706-6132 E-mail: *tomioka@rciqe.hokudai.ac.jp

Abstract

InGaAs nanowires (NWs)/Ge heterojunction tunnel diodes were demonstrated by selective-area growth of InGaAs NWs on *p*-Ge substrates. Vertical-aligned InGaAs NWs with various In composition (In content: 35 – 95%) were heterogeneously integrated on Ge(111) substrates. The InGaAs NW/*p*-Ge heterojunction with a few misfit dislocation exhibit Esaki tunneling process due to Type-II band discontinuity. Demonstrated InGaAs NW/Ge tunnel diode showed negative differential resistance (NDR) at 0.1 V with a high current density (~ 30 kA/cm^2).

1. Introduction

Primary challenges in future electronics is to reduce power consumption while enhancing their performance. III-V compound semiconductor and Ge are expected alternative fast channel materials for the future electrical switches [1]. Among the III-V, InGaAs with In composition of 53 – 80% has good electrostatic gate controllability and feasible for next generation n-type field-effect transistors (FETs). Miniaturization of metal-oxide-semiconductor FETs (MOSFETs) is reaching to several nanometer-scale and such ultimate-scaling would lead a bottleneck in III-V and Ge FETs because there is no effective approach of integrating both III-V and Ge on Si platforms with this scaling node. And, mobility mismatch emerges as a new problem in terms of the miniaturization. We, therefore, proposed the hybrid logic architecture using vertical III-V nanowire (NW) channel directly integrated on p-type Ge MOSFETs because the vertical architecture can shrink their effective device area compared to the planar architecture and enables an equivalently down scaling of the n-type MOSFETs [2].

Equally, multijunction solar cells combining III-V and Si [3] or Ge are expected for high energy conversion efficiency. With this regard, the InGaAs NWs with In composition of 10 – 20% integrated on Ge would realize the dislocation-free multi-junction tandem solar cells because selective-area growth of the thin NWs would suppress the lattice relaxation due to formation of misfit dislocation. And this suppression of lattice relaxation realize high quality tunnel junction composed of InGaAs middle and Ge bottom cell regardless of any buffer or graded layer.

Here we report on the heterogeneous integration of InGaAs NWs with various In composition in terms of composition controllability of the NWs for FET and photovoltaic applications. We found that the InGaAs NW/p-Ge junction by the NW-synthesis exhibit good tunnel junction without any heavy doping, showing Esaki band-to band tunneling process. The Esaki tunnel diode using the InGaAs NW/Ge junction demonstrated high current density with a large NDR at 0.11 V.

2. Experimental

2.1 Selective-area MOVPE of InGaAs NWs on Ge

The Ge(111) was Ga-doped p-type substrate, whose carrier concentration of 2 × 10^{18} cm^{-3}. 20 nm-thick SiN film was deposited by ECR-CVD. Then, openings were formed by EB lithography and dry/wet etchings. The openings were 30 nm in diameter. The InGaAs NWs were grown by MOVPE with H_2 carrier gas. Trimethylgallium (TMGa), trimthylindium (TMIn), and arsine (AsH_3) gas were used as precursors. And monosilane (SiH_4) and tetraethyltin (TESn) were used as n-type dopings. Diethylzin (DEZn) were used for p-type dopants. The initial Ge(111) surface was exchanged to (111)B-polar surface [4,5] to align vertical InGaAs NWs on Ge(111). The InGaAs NWs were grown under different In composition in vapor phase from 18 – 60% at 670°C with constant V/III ratio of 88. The NWs was composed of Zn-doped/Si-doped InGaAs/Sn-doped InGaAs layer. Zn and Sn doped layer were grown by pulse doped technique [6,7].

2.2 Device process for NW-diodes

A two terminal device was fabricated for characterization of electrical properties in InGaAs NW/Ge interface by first coating the NWs with benzocycrobutene (BCB) by spin-coating. Then, 30 nm length of InGaAs NW were revealed by reactive-ion etching with using O_2/CF_4 mixed gas. Next, 10 nm-thick Ni/10 nm-thick Ge/50 nm-thick Au was evaporated on top of the NWs and 15 nm-thick Ni/50 nm-thick Au was deposited on backside of the Ge substrates. The devices were annealed at 250°C for 3 min in N_2.

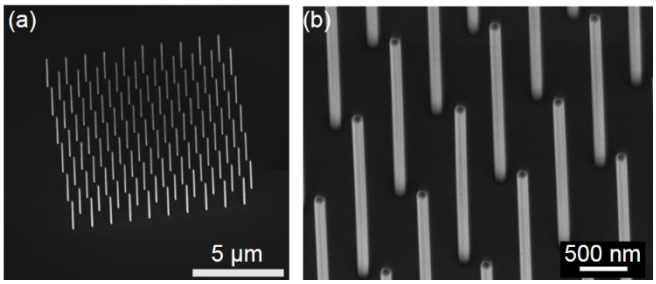

Figure 1(a) SEM image showing InGaAs NW array directly grown on Ge(111) substrate. (b) InGaAs NWs were 3.2 μm in length, and 100 nm in diameter (in average)

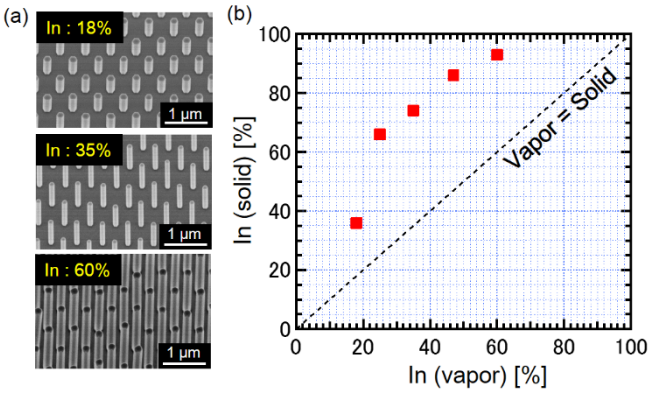

Figure 2(a) SEM image showing InGaAs NWs on Ge(111) grown with various In composition in vapor phase. (b) In content in NW solid-phase with a variation of In composition in vapor phase.

3. Results and Discussion

Figure 1 shows representative growth result of the vertical $In_{0.7}Ga_{0.3}As$ NWs on *p*-Ge(111). The In composition in vapor phase was 25% and that of solid phase was approximately 70%. The NWs were perfectly aligned in vertical <111> direction (normal to the substrate) because of the formation of (111)B-polar surface. The NWs were 3.2 μm in length and 100 nm in diameter. Each NW was composed of Sn-doped contacting layer (300 nm-length)/Si doped segment (2.5 μm-length)/Zn-pulse doped segment (400 nm-length) in axial direction.

To investigate composition controllability for the FET and solar cell devices, In composition in solid phase of the NWs grown under various In composition in vapor phase were characterized by XRD profiles. Figs. 2(a) and (b) exhibit representative growth results and the variation of In composition in solid phase, respectively. The composition was estimated from the InGaAs peaks of XRD 2θ-ω profile. The In composition in solid phase was varied from 36 to 93%, which was larger than those in vapor phase. And the solid-phase composition was sublinearly increased with the vapor phase composition. This was because that surface diffusion length of In adatoms on NW-sidewalls was longer than that of Ga adatoms and As-timer on (111)B top facet suppressed incorporation of Ga atoms. In case of Ga-rich InGaAs (Ga: 10 – 20%), the tendency closed to that of selective-area growth of GaAs NWs since the optimum growth temperature was increased to 730°C. This seemed to relate with nucleation and desorption of the group-III source materials, In/Ga atom, which was closed to the nucleation-limited growth of ternary III-V NWs by self-catalyzed VLS [8].

Figure 3(a) shows current density (J_D)-voltage (J_D-V) curve of the fabricated *n*-$In_{0.7}Ga_{0.3}As$ NWs/*p*-Ge vertical diodes measured at room temperature. Inset depicts the device schematics indicating the *p*-Ge was grounded. The diode using $In_{0.7}Ga_{0.3}As$/Ge junction exhibit moderate rectifying property whose turn-on voltage of 0.76 V in the forward bias direction, indicating the band discontinuity of the junction is Staggared Type-II band discontinuity with the conduction band offset of 0.76 eV. And the diode demonstrated very high J_D (230 kA/cm^3) at -1.0 V. Interestingly, the NDR property

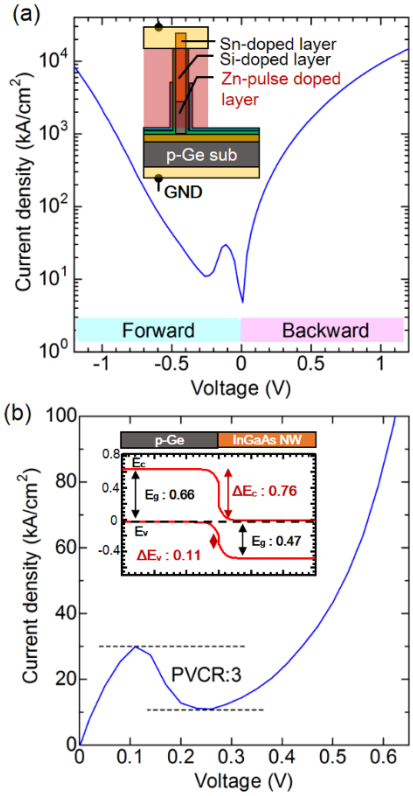

Figure 3 (a) Semi-log plot of J_D-V curve. Inset illustrates diode structure. (b) NDR properties of the InGaAs NW/Ge Esaki tunnel diodes.

due to band-to-band Esaki tunneling was observed at around -0.11 V. This means that direct growth of the $In_{0.7}Ga_{0.3}As$ NWs on p-Ge substrate naturally forms a heavy-doped layer in the vicinity of the $In_{0.7}Ga_{0.3}As$ NW/*p*-Ge interface to thinning the tunnel junction width. The origin of the heavy-doping was assumed to be Ge- and group-III atoms interdiffusion during the NW synthesis, that is, Ge atoms were thermally diffused into the $In_{0.7}Ga_{0.3}As$ NW and group-III (In or Ga) atoms were diffused inside the Ge. When the tunnel junction width is 00 nm, the carrier concentration of each layer around the heterojunction is estimated as 2.0×10^{19} cm^{-3}. Further characterization of the localized dopants will be required.

Figure 3(b) shows that peak current density (PCD) was 30 kA/cm^{-2} and peak-to-valley ratio (PVCR) was 3, which were slightly higher than those of Si/SiGe-based resonant tunnel diodes (RTDs) [9]. This imply that the InGaAs/Ge tunnel junction would reasonably utilized in BJT technologies for high frequency operation once the Si CMOS platforms is replaced with InGaAs/Ge. Menawhile, such new tunnel junction should be feasible for InGaAs/Ge tandem solar cells.

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