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Present Status and Future Issues of III-V Semiconductor Nanowires

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1. Introduction

Semiconductor nanowires have become a focus of attention over the past several years because they have shown potential for developing nanostructure devices that might be used in future electronics. Before the 1980s, free-standing semiconductor wires made using whiskers were the focus of interest in crystal structure analysis and growth mechanism studies [1-3]. Ever since the 1990s, when the gate length of a Si MOS-FET was reduced to 100 nm or shorter, much attention has been paid to low-dimensional electronic and optical devices that operate by means of quantum mechanical effects and that might be superior to conventional devices. We have reported on the growth characteristics of GaAs, InAs, and AlGaAs nanowires obtained using the whisker growth method [4, 5]. To make a nanowire device by using whiskers or other semiconductor materials, it is very important to control the growth site and size on a substrate surface and to minimize the surface effects of the nanostructure. Regarding the control of whisker growth position and size, we demonstrated a growth method using a SiO_2 window pattern fabricated by electron beam lithography [6]. In this process, Au alloy drops used as a growth catalyst were formed within the SiO_2 window region of a GaAs substrate surface. Whiskers were grown using the vapor-liquid-solid (VLS) method during organometallic vapor-phase epitaxy (OMVPE). A nanowire FET composed of site-controlled InAs whiskers was reported in order to show the importance of using the electron beam lithography [7]. Recently, a new method for growing GaAs nanowires without using any growth catalyst has been reported [8]. The growth position of the nanowires was controlled using a SiO_2 mask pattern. However, there has been serious concern about surface effects in nanowires, which might be an obstacle to device operation in practical use. In the conference, we will explain the basic growth characteristics of GaAs whiskers obtained by VLS growth during OMVPE and discuss electrical and optical properties in relation to future issues of III-V semiconductor nanowires.

2. Experimental

GaAs whiskers were grown using trimethylgallium (TMG) and arsine (AsH_3) as source materials. Si_2H_6 (5 ppm in H_2) was used as an n-type dopant. The sources were flowed into the SiO_2 reaction chamber of an OMVPE system by using H_2 as a carrier gas. The total pressure inside the reaction chamber was maintained at 2.0 x 10^5 Pa. We used semi-insulator and n-type GaAs (111)B substrates. The substrate was placed on a graphite disc, which was heated by RF induction. Before the substrate was put into the OMVPE chamber, Au was deposited on the GaAs substrate surface by vacuum evaporation. The target thickness of Au deposition was changed between 0.1 and 10 nm. The schematic growth process of whiskers is shown in Fig. 1. The substrate was heated to 500°C in an AsH_3 and H_2 atmosphere to form Au-Ga alloy drops on the substrate surface. GaAs whiskers were then grown at temperatures between 380 and 500°C by supplying TMG with AsH_3. To analyze the surface effects of GaAs whiskers, we measured photoluminescence (PL) spectra of samples with and without $(NH_4)_2S$ treatment (sulfur treatment). To investigate electronic properties, we fabricated a two-terminal device containing Si-doped GaAs whiskers (doping level: ca. 1 x 10^{18} cm^{-3}) and measured the current-voltage (*I-V*) characteristics.

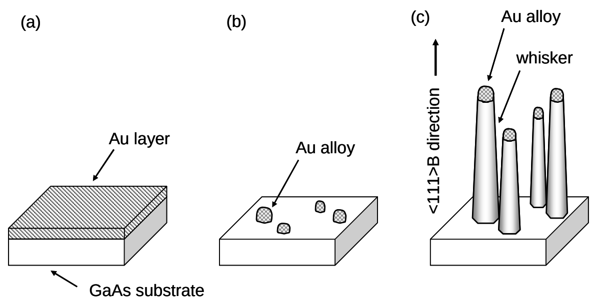
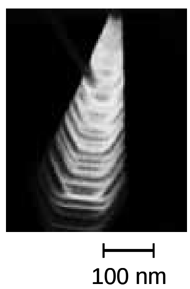


Fig. 1 Schematic growth process of whiskers. (a) Au deposition on GaAs(111)B substrate. (b) Au alloy formation during heat treatment of substrate. (c) Whisker growth by OMVPE.

3. Results and discussion

A scanning electron microscope (SEM) image of a GaAs whisker is shown in Fig. 2. The whisker diameter is about 20 nm at the tip and 200 nm around the base: the length is around 1-2 μm.



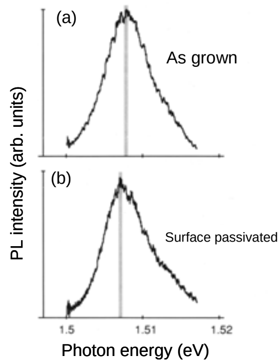


Fig.2 SEM image of whisker.

Fig. 3 PL spectra of GaAs whiskers.

Figure 3 shows PL spectra measured at 77 K for non-doped GaAs whiskers before and after sulfur treatment. The PL spectra indicate a spectral red-shift of 0.8 meV after the treatment. This red-shift suggests that quantum confinement of carriers in the GaAs whiskers was dominated by the depletion potential. The effect of the depletion potential has also been found in the recombination dynamics of GaAs whiskers before and after surface treatment [9]. Figure 4 shows an SEM image of Si-doped GaAs whiskers selectively grown on GaAs (111)B substrate surface and a schematic cross-sectional view of a fabricated device composed of many whiskers.

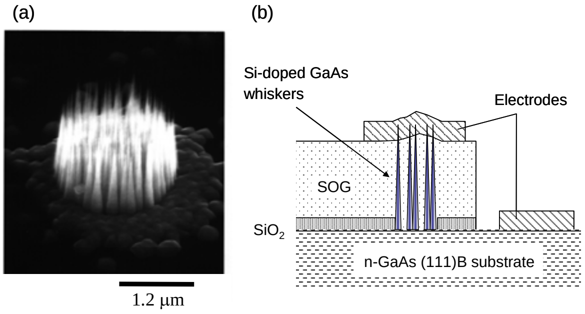


Fig. 4 SEM image of GaAs whiskers and schematic view of whisker device. (a) Bird's eye view of whiskers. (b) Cross-sectional structure of device.

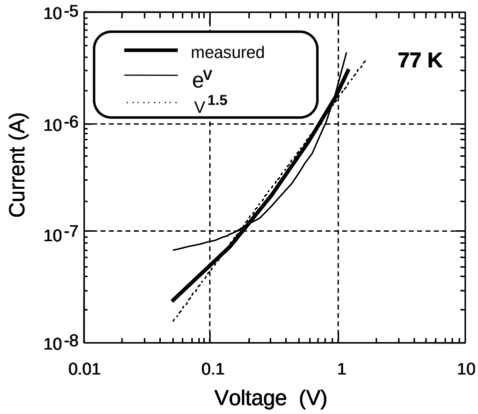


Fig. 5 Current-voltage (I-V) characteristics measured for whisker device. Calculated I-V curves approximated by the forms of e^V and $V^{1.5}$ are also plotted.

I-V characteristics measured at 77 K for the whisker device are shown in Figs. 5 and 6. The measured I-V curve was compared with the calculated ones for the applied voltage range of 0.1-1.0 V. We found that the measured I-V curve was better approximated by the polynomial form of $V^{1.5}$ rather than the exponential form of e^V, suggesting that a space-charge region was formed in the whiskers [10]. We observed step-like current fluctuations as the voltage was increased from 1.0 to 1.7 V, as shown in Fig. 6. The current fluctuation suggests that carriers were captured by a surface-trapping level of the whisker and released from the level by the change in applied electric field. These results indicate that we should consider surface stabilization to avoid unstable I-V characteristics in practical applications.

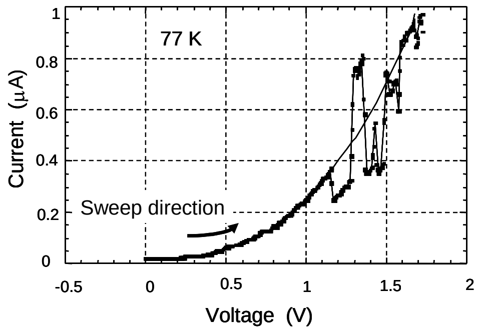


Fig. 6 I-V characteristics of whisker device.

4. Summary

We have measured photoluminescence (PL) and current-voltage (I-V) characteristics of GaAs whiskers grown by organometallic vapor-phase epitaxy in combination with the vapor-liquid-solid method. The PL peak energy shifted by 0.8 meV toward the lower energy region after sulfur treatment of the whisker surface. The I-V measurement showed a step-like current change, suggesting that carriers were affected by trapping levels in the whisker. These experiments indicate that we need to stabilize the whisker surface for practical application.

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