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Electrical Properties of Ge-Doped InSb and InAs on GaAs(111)A Substrate

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1. Introduction

The electrical properties of Ge-doped InSb and InAs on GaAs(111)A substrates grown by molecular beam epitaxy (MBE) are investigated by Hall-effect measurements. InSb and InAs have been proposed for use in high performance devices (high sensitivity magnetic sensors, high frequency devices, infrared applications, etc.) because of their high electron mobility and narrow band gap. Since the hetero-interfaces between InSb / GaAs (14.6%) and InAs / GaAs (7.2%) have large lattice mismatch, layer-by-layer growth of high-quality InSb and InAs thin films on GaAs substrates is extremely difficult. However, when the InAs epitaxial layers are grown on GaAs (111)A substrates, the dislocations due to the lattice mismatch are confined near the interface. As a result, two-dimensional layer growth takes place, and the InAs layers with abrupt interfaces are obtained [1]. A similar effect has been reported for the growth of InSb layers on GaAs (111)A substrates [2].

Germanium is known to be one of the amphoteric impurities in III-V compound semiconductors, and the doping characteristics depend upon the growth conditions. It is well known that for heavily Ge-doped (>$1x10^{19}cm^{-3}$) GaAs layers grown by MBE, the almost all the Ge atoms are incorporated into acceptor sites. While, for lightly Ge-doped sample, Ge atoms are incorporated into donor sites. In this study, we have investigated Ge-doping characteristics in InAs and InSb grown on GaAs (111)A substrates. Very different results have been observed in these materials. For InAs, heavily Ge-doped layers exhibit n-type conductivity whereas lightly doped samples show p-type conductivity. For InSb, the layers show p-type conductivity regardless of the doping level. These characteristics are discussed in this paper.

2. Experimental procedure

Ge-doped InSb and InAs films are grown on GaAs (111)A substrate by MBE method. GaAs substrates are first etched in an alkaline etchant and loaded in the growth chamber. The native oxide layers of the GaAs surface are removed by a thermal flash at 580°C in As_4 atmosphere, and then 500-nm-thick GaAs buffer layer is grown at 500°C.

After GaAs buffer layer growth, low temperature InSb buffer layer with 5nm thickness is grown at 315°C, and the substrate temperature is increased to 390°C without growth interruptions [2]. The growth rate and the grown thickness of InSb are fixed at 0.26μm/h and at 0.4μm, respectively. The beam equivalent pressure (BEP) ratio of [Sb_4 / In] is 5, and Ge-cell temperature is varied between 700°C and 1000°C.

1-μm-thick InAs films are grown at 400°C with the growth rate at 0.33μm/h. The BEP of As_4 is approximately at $1.5x10^{-5}$ Torr, and Ge-cell temperature is varied in the same range of InSb growth.

Reflection high-energy electron diffraction (RHEED) patterns are monitored during the growth. The electrical properties are investigated by Hall-effect measurement using the van der Pauw method at temperatures ranging from 10K to 300K in the dark. Indium metals are soldered onto the as-grown sample surfaces in N_2 atmosphere to obtain ohmic contacts.

3. Results and Discussions

During the growth of the InSb and InAs layers on GaAs (111)A substrates, the RHEED patterns are streaky from the initial stage of growth. The resulting surfaces and heterointerfaces are very flat compared with those grown on GaAs (001) substrates.

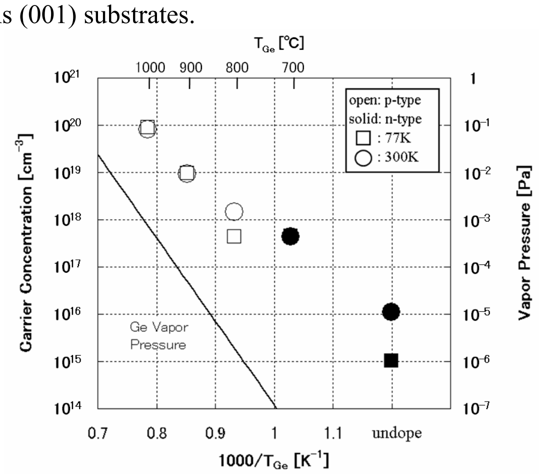

Fig.1. Carrier concentrations at 77K and 300K of Ge-doped InSb films on GaAs (111)A as a function of reciprocal Ge-cell temperatures. Open and solid symbols show the p-type and n-type, respectively.

Figure 1 shows the measured carrier concentrations at 77K and 300K of Ge-doped InSb films grown on GaAs (111)A as a function of reciprocal Ge-cell temperatures. Open symbols denote p-type, and solid symbols show n-type. Squares are the results measured at 77K, and circles express the data measured at 300K. The layers grown with 800-1000°C Ge-cell temperatures show p-type conductivity and the hole concentration dependence of the Ge-cell temperature coincides well with the Ge vapor pressure curve as shown in Fig.1. This means that Ge-doping concentration is proportional to the Ge flux.

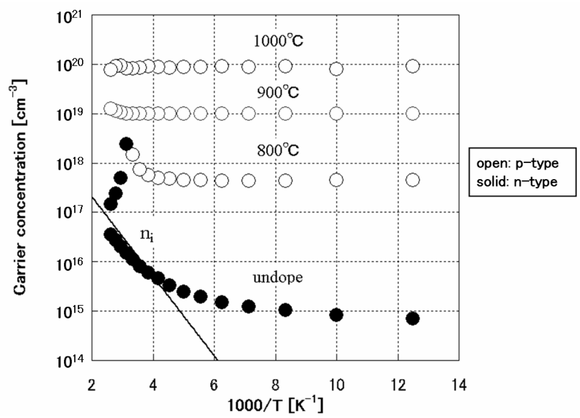

Fig.2. Temperature dependence of the carrier concentration of Ge-doped InSb films grown at several Ge cell temperatures.

Figure 2 shows the temperature dependence of the carrier concentration of Ge-doped InSb films. The sample grown with the 800°C Ge-cell temperature changes from p-type to n-type when the sample temperature exceeds 320K. This inversion suggests the contribution of intrinsic carrier concentration and the high mobility of electrons. At the same time, the temperature dependence of the carrier concentration implies the existence of parallel conductions. The hole concentration of the layers grown with 900-1000°C Ge-cell temperature is almost constant in the wide range of sample temperatures.

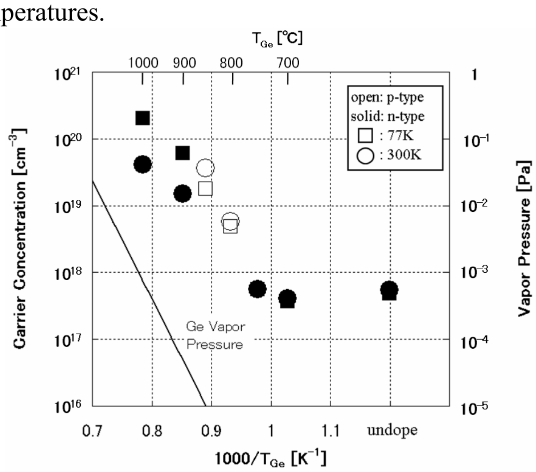

Fig.3. Carrier concentrations at 77K and 300K of Ge-doped InAs films on GaAs (111)A as a function of Ge-cell temperatures.

Figure 3 shows the carrier concentrations at 77K and 300K of Ge-doped InAs films on GaAs (111)A. The layers grown with the 800-850°C Ge-cell temperatures show p-type conductivity. While, the those grown with 900-1000°C Ge-cell temperatures exhibit n-type conductivity. The Ge-doping concentration of the layer grown with 900°C Ge-cell temperature is estimated to be $6x10^{19}cm^{-3}$. It is suggested that high concentration doping makes carrier type inverted to n-type.

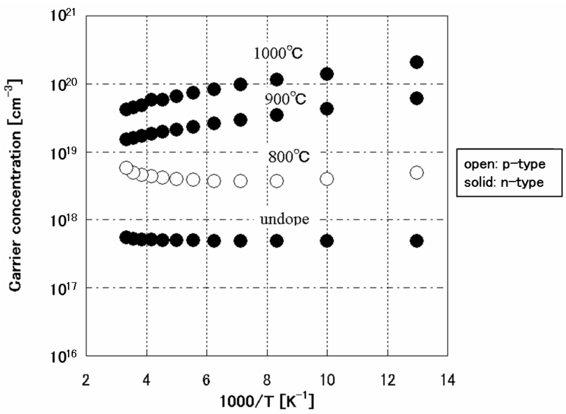

Fig.4. Temperature dependence of the carrier concentration of Ge-doped InAs films grown at several Ge cell temperatures.

Figure 4 shows the temperature dependence of the carrier concentration of Ge-doped InAs films. The activation energy of hole concentration of the layer grown with 800°C Ge-cell temperature coincides with the ionization energy of Ge acceptor in InAs bulk. The electron concentration decreases for the sample grown with 900-1000°C Ge-cell temperature when the sample temperature increases. This suggests that high concentration doping induces deep traps that are activated at high sample temperature.

4. Conclusions

The electrical properties of Ge-doped InSb and InAs on GaAs(111)A substrates are investigated by Hall-effect measurement. InSb and InAs films grown on GaAs (111)A substrates have high crystalline quality, and they have abrupt substrate-epitaxial layer interfaces. The Ge impurity acts as an acceptor in InSb grown on GaAs (111)A, and Ge is confirmed to be a good acceptor for InSb on GaAs (111)A. For lightly doped layers($<2x10^{19}cm^{-3}$), InAs layers show p-type conductivity. While, for heavily doped layers ($>6x10^{19}cm^{-3}$), they show n-type conductivity. The high concentration doping of Ge into InAs makes conduction type change from p-type to n-type.

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