Air-Gap Capacitance-Voltage Analyses of InP Surfaces after Wet and Dry Processes

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1. Introduction

Control of the surface and interface of III-V semiconductors has recently become vital for realizing high-mobility n-channel MOSFETs on the Si platform. P-type InP is one of the materials considered because of its high electron mobility and large energy gap.

In this paper, p-InP surfaces treated with wet and dry processes were characterized using air-gap capacitance-voltage (C-V) technique. XPS measurements were also carried out.

2. Air-gap capacitance-voltage analysis^[1,2]

The schematic view of this system is shown in Fig. 1. Instead of depositing a gate electrode, C-V measurements were performed at the field electrode separated from the sample surface by a thin air gap (~300 nm). Due to the presence of the air-gap insulator, the C-V analysis of free or ultrathin insulator covered surfaces becomes possible without suffering from leakage current. In this study, Cr was used for the electrodes, the area of the measurement electrode was 7.5 x 10^{-3} cm², and the measurement frequency and bias sweep speed were 0.5 MHz and 1.0 V/s, respectively.

3. Sample preparations

P-InP epitaxial layers ($N_A \sim 6 \times 10^{15} \text{ cm}^{-3}$, 3 µm) grown on p⁺-InP substrate were used, which were kept in an air atmosphere resulting in the presence of natural oxide (*as received*). First, the surface was immersed in dilute HF solution for 5 min (HF: H₂O = 1: 2) (*HF treated*). Then the surface was treated with NH₃ (28%) solution^[3] for 10 min (*NH₃ treated*). Finally, the sample was exposed to N₂-radicals for 10 min in a vacuum chamber (RF power: 150 W, T_{sub}: 350 °C) (*N₂-rad.-treated*).

4. Results and discussions

The air-gap C-V characteristics of *as received*, *HF treated*, and *NH*₃ *treated* surfaces are shown in Figs. 2(a), (b), and (c), respectively. Curves show deep-depletion behavior and large and distinctive hysteresis. The hysteresis feature is as follows: when the bias direction was changed at V = -30 V (or -60 V), the capacitance value began decreasing immediately without retracing the curve. To explain this behavior, a donor-like discrete level was introduced^[4] as shown in Fig. 3. Regions A, B, and C correspond to those in Fig. 2(c). In region A, the discrete level was filled with electrons and electrically neutral. In region B, the Fermi level was pinned causing the emission of electrons. Here, donor-like traps without electrons became positively charged. In case these empty







Fig. 2 Air-gap C-V curves for (a) as received, (b) HF treated and (c) NH_3 treated p-InP surfaces.

traps were not filled with electrons even if the applied voltage increased, which acts as positive fixed charge, the immediate decrease of capacitance value occurred as observed in Figs. 2(a), (b), and (c). The fitting result obtained by solving a one-dimensional Poisson's equation including the discrete level mentioned above is shown in Fig. 2(b). A good agreement was obtained. From other analysis^[5], the amount of the discrete level is larger than 1 x 10¹³ cm⁻²eV⁻¹. Figure 4(a) shows the air-gap C-V curve for the N_2 -rad.-treated surface. The dashed and



Fig. 3 Behavioral model to explain the air-gap C-V curves shown in Fig. 2.





solid lines are calculated curves using the surface state density distributions shown in Fig. 4(b). Energy positions α and β in Fig. 4(b) correspond to measurement points in Fig. 4(a). After N₂-radical exposure, the density of the discrete level decreased and the Fermi level could move beyond it; on the other hand, a continuous level was observed. The mismatch between the measured and calculated curves under bias direction of negative to positive can be explained from the other analysis resulting in faster electron injection to the discrete level.^[5]



Fig. 5 (a) Oxide and (b) nitride components normalized by bulk signals for each surface process step obtained from XPS measurements.

To investigate this variation of surface state density distribution. surface chemical components were characterized using an XPS measurement system consisting of a spherical capacitance analyzer and a monochromated Al $K\alpha$ x-ray source (hv=1486.6 eV). The electron escape angle was $10^\circ\,$, which was sensitive to the surface. Figures 5(a) and (b) show the change of the oxide and nitride components after each surface process step. The P-oxide component was decreased markedly by the HF treatment. On the other hand, it is known that the In-oxide component is difficult to remove; however, N₂-radical treatment reduced it effectively. With regard to the nitride component, the P-nitride component was produced after NH₃ treatment, while it was removed by N₂-radical treatment, but the In-nitride component was produced after N₂-radical treatment. The details of the mechanism are not clear yet; however, the cleaning effect of the oxide component and/or the formation of the In-nitride component possibly affected the reduction of the discrete level after N₂-radical treatment. It can be said that the variation of the surface state density distributions related to the surface chemical components is successfully characterized by a combination of air-gap C-V and XPS measurements.

Conclusion

From air-gap C-V analyses, it is indicated that there is high density discrete level at the *as received* p-InP surface. To reduce this, N₂-radical exposure was effective while HF- and NH₃-treatments had no effect. The cleaning effect of the oxide component and/or the formation of the In-nitride component possibly affected it.

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