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1.8kV AlGaAs/GaAs/AlGaAs Diode Having Balanced Charges of Donors and Acceptors in Consideration of Residual Carbon Impurities

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Abstract

AlGaAs/GaAs/AlGaAs diodes with a pair of hole and electron channels have been studied. The hole channel was formed taking into account residual acceptors. The acceptor sheet concentrations (N_A) were doped from 0.8 to 1.0×10^{12} cm^{-2} with a fixed donor sheet concentration of 1.1×10^{12} cm^{-2}. The diode with N_A of 0.9×10^{12} cm^{-2} derived the highest breakdown voltage (BV) of 1800 V for a 113 µm drift region length. The highest BV was found to be due to avalanche multiplication. The diode also showed the lowest voltage of complete depletion of both channels through C-V characteristics. Consequently, the same concentration of donor and acceptor including residual impurity delivered the high BV.

1. Introduction

Superjunction (SJ) structure in a power device can overcome the trade-off relation between low on-resistance and high breakdown voltage (BV) [1]. Silicon SJ devices compose p-type pillars in the n-type drift layer. The same concentration of acceptor and donor in the drift layer is essential to obtain a high BV due to simultaneous depletion of holes and electrons. Meanwhile, a tiny unbalance between the acceptor and donor concentrations decreases BV drastically [2].

In order to increase BV against the silicon SJ devices, we study on an AlGaAs/GaAs/AlGaAs structure with a pair of hole and electron channels [3-5]. GaAs is an attractive material due to its mature process, easy doping control, and good crystallinity as compared to other compound semiconductors. The transistor modulation characteristic by a four-terminal test device was reported [3]. However, the diodes didn't show a sufficiently high BV [5]. The breakdown electric field was lower than the critical electric field of GaAs. Through the analysis of the channels, we found that the hole concentration was not the same as the electron concentration due to some amount of residual impurities. Carbon is an acceptor which is a residual impurity in GaAs and AlGaAs grown by metal organic chemical vapor deposition (MOCVD). The acceptor concentration is about 10^{15} cm^{-3} [6].

The purposes of this study are to investigate the effect of residual impurities on breakdown characteristics, and to achieve high BV. In consideration of residual impurities, precise doping design is a key point. A high BV is examined in terms of simultaneous depletion of hole and electron channels.

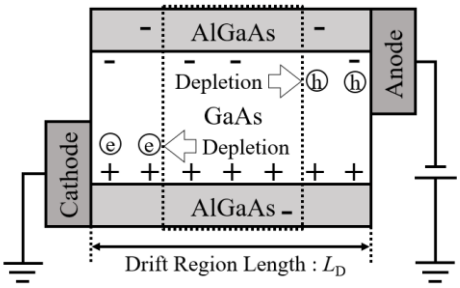

Fig. 1 Cross-sectional schematic of AlGaAs/GaAs/AlGaAs hetero-structure diode with a pair of hole and electron channels. The drift region length (L_D) was the distance between the electrodes. The hole and electron channels are depleted toward each electrode in increasing reverse voltage.

2. Epitaxial wafer and diodes fabrication

The test device with an oval shape [3] was not suitable for breakdown measurement. In this study, we fabricated a circular diode, where a center electrode was an anode surrounded by a cathode. Figure 1 shows the cross-sectional schematic of the circular diode for breakdown measurement. The anode diameter is 400 µm, and the drift region lengths (L_D) are 53, 83, and 113 µm. For C-V measurement, the diameter is 500 µm with 3 µm L_D.

AlGaAs/GaAs/AlGaAs heterostructure wafers were grown by MOCVD on a semi-insulated GaAs substrate. The epitaxial layer consists of 400 nm $Al_{0.3}GaAs$, 600 nm GaAs, and 400 nm $Al_{0.3}GaAs$/GaAs superlattice. The GaAs layer includes a pair of hole and electron channels at the interface of the AlGaAs layers, respectively. Silicon donor was doped to the concentration of 1.1×10^{12} cm^{-2} for the electron channel formation. Then, acceptor doping concentrations (N_A) of 0.8, 0.85, 0.9, 0.95, and 1.0×10^{12} cm^{-2} were doped to form the hole channel. For determination of N_A, the residual acceptor concentration was characterized in advance. The residual concentration in AlGaAs was found to be 3×10^{15} cm^{-3}. That in GaAs was less than 10^{14} cm^{-3}. The sheet concentration of the residual acceptor was obtained to be 0.2×10^{12} cm^{-2}.

For the diode fabrication, SiO_2 films were deposited on the wafers by atomic layer deposition (ALD). The drift region was isolated by H_2SO_4 etchant using the SiO2 mask. For the cathodes formation, AuGe/Ni were evaporated and annealed, then the anodes were formed by AuZn/Ni. Finally, SiO_2 passivation was deposited by ALD. Subsequently, diodes for breakdown measurement were mounted on Au/Ni plated ceramic packages using silver paste. The diodes were bonded to the packages with Al wires and sealed with epoxy resin.

3. Result and Discussion

The reverse current-voltage characteristics of the packaged diodes were measured. Figure 2 shows a breakdown voltage dependence on N_A for the diodes with L_D of 113 µm. The BV is defined as the voltage where the reverse current reaches 10 µA/mm. The median values of BV were derived from five to nine diodes. Low median BVs were observed at low and high N_A of 0.8 and 1.0×10^{12} cm^{-2}, respectively. On the contrary, median BVs were high between the low and high concentrations. Especially, the maximum BV (BV_{max}) of 1800 V was obtained at 0.9×10^{12} cm^{-2} N_A. Figure 3 shows breakdown characteristic of the 113 µm L_D diode with 0.9×10^{12} cm^{-2} N_A, and those of 53 and 83 µm L_D diodes as insertion. The reverse current is normalized by the anode circumference. BV increased in proportion to L_D as 900, 1300, and 1800 V. The average electric fields of the three diodes were about 0.16 MV/cm. This value is similar to the critical electric field of GaAs. Temperature dependence of the diode BV was characterized, and showed a positive coefficient. We have found that BV is dominated by avalanche multiplication and not determined by the localized high electric field.

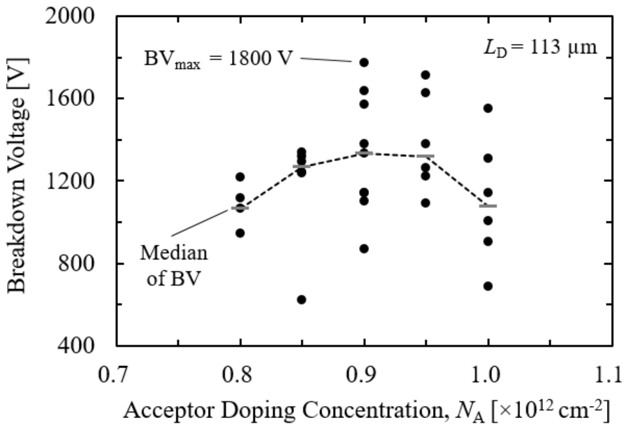

Fig. 2 Breakdown voltage dependence on N_A for the diodes with L_D of 113 µm. The BV was defined at the reverse current of 10 µA/mm. Five to nine diodes with the same N_A were measured. The medians of BV are shown as gray bars, and connected by a broken line.

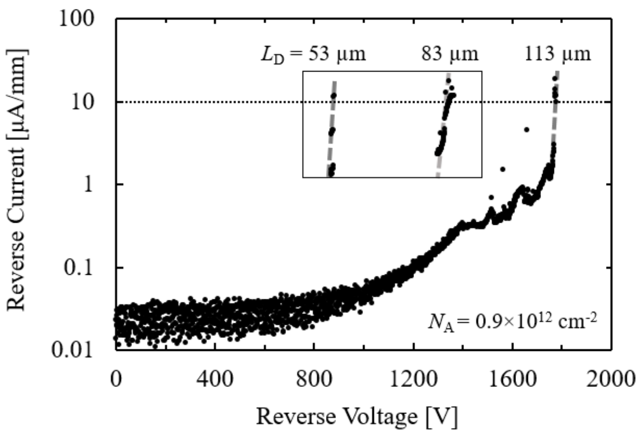

Fig. 3 Breakdown characteristic of the 113 µm L_D diode (BV_{max} = 1800 V). The inset shows breakdown characteristics for the diodes with L_D of 53 µm (900 V) and 83 µm (1300 V). N_A is 0.9×10^{12} cm^{-2}.

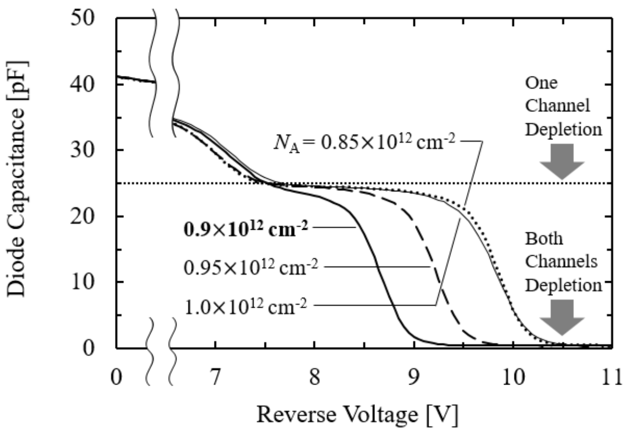

Fig. 4 C-V characteristics of the diodes with N_A from 0.85 to 1.0×10^{12} cm^{-2}. Two capacitance drops were observed in C-V curves depending on elimination of the hole and/or electron channels. The 0.9×10^{12} cm^{-2} N_A diode was completely depleted at the lowest voltage.

C-V measurements were performed to characterize channel depletion. Figure 4 shows C-V characteristics of diodes with N_A from 0.85 to 1.0×10^{12} cm^{-2}. All diodes showed 40 pF at 0 V and 25 pF at 7.5 V. Abrupt drops of diode capacitance were observed below 25 pF. Distinct drop voltages were seen for different N_A. For the 0.9×10^{12} cm^{-2} N_A diode, the drop voltage was the lowest, and would be due to simultaneous depletion of both channels. On the other hand, the diodes with a higher and lower concentration of 0.9×10^{12} cm^{-2} showed the higher reverse voltage. The C-V measurement is sensitive to detect channel depletion. It can be concluded that the total concentration of 0.9×10^{12} cm^{-2} N_A and the residual acceptor is the same as the donor concentration, thus resulting in high BV.

4. Conclusions

AlGaAs/GaAs/AlGaAs diodes with a pair of hole and electron channels were studied. The effect of residual impurities on breakdown characteristics was investigated. The highest BV of 1800 V was obtained by the 113 µm L_D diode with the 1.1×10^{12} cm^{-2} donor concentration and 0.9×10^{12} cm^{-2} N_A taking into account the residual acceptor. C-V characteristics revealed simultaneous depletion of both channels. We have established a doping design considering the same concentration of donor and acceptor including residual impurity, that can achieve high BV.

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