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Study of minority-electron transport through atomic-diffusion-bonding InGaAs/a-Ge/InGaAs interface using photodiode structures

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Abstract

We experimentally investigated minority-electron transport through wafer-bonding InGaAs/a-Ge/InGaAs interfaces by using a uni-traveling-carrier photodiode (UTC-PD) structure. The C-V characteristics and DC and O/E response were compared with those of a conventional UTC-PD, which revealed that the electric field is concentrated in the vicinity of the bonding interface when bias voltage is applied to the PD. From the O/E response, it was found that the minority-electron transport through a bonding interface is similar to that of the conventional PD without a bonding interface.

1. Introduction

Wafer-bonding techniques have the potential to expand semiconductor material choice, which has been restricted by the lattice-matching condition, and thus improve semiconductor device performance, such as thermal conductivity, breakdown voltage, and O/E conversion efficiency. To date, improvements in thermal conductivity and solar-cell efficiency with wafer-bonding techniques have been demonstrated with the aim of fabricating devices that include lattice-mismatched epitaxial layers [1, 2].

One of key issues in expanding the applicability of wafer-bonding techniques to various semiconductor devices is the effect of the bonding on their operation speed. In particular, understanding minority carrier behavior through a bonding interface is important for the design of high-speed devices, such as transistors, optical modulators, and photodiodes.

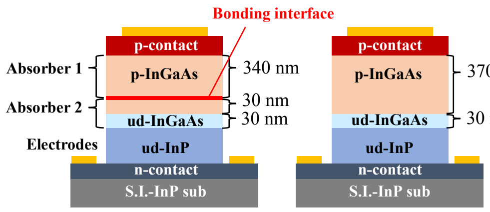
In this study, using a photodiode structure, we experimentally investigated minority-electron transport through an atomic-diffusion-bonding (ADB) InGaAs/a-Ge/InGaAs interface by examining the bias voltage dependence of capacitance, photocurrent, dark current, and O/E response.

2. Sample structures and fabrication

To investigate the minority carrire behavior through the bonding interface, we employed two UTC-PD structures as shown in Fig.1(a) and (b). The active layer of each UTC-PD consists of a neutral (p-type) light absorber and an undoped InP carrier-collection layer. Different from a conventional PD, the operating speed of UTC-PD is determined by electron transport because holes behave as majority carriers [3]. The minority electrons excited in the absorber move toward the n-type contact layer.

We prepared a UTC-PD with bonding interfaces (ADB-PD), as shown in Fig. 1 (a). In order to clarify the effect of the bonding interface on minority-electron transport, we also prepared a conventional UTC-PD (REF-PD) as a reference without a bonding interface as shown in Fig. 1 (b).

To fabricate an ADB-PD, we prepared two epitaxial wafers (a P-side wafer and an N-side wafer) grown on a semi-insulating InP substrate by MOCVD. The P-side wafer consists of a p-contact layer and a p-type InGaAs absorber. The N-side wafer consists of an n-contact layer, an undoped InP layer, an undoped InGaAs layer and a p-InGaAs absorber. After the epitaxial growth, the two wafers were bonded to each other with 2-nm-thick a-Ge adhesive by using the ADB technique, which features low-bonding damage [4]. After the bonding of the P- and N-side wafers, the InP substrate of the P-side wafer was removed by polishing. Finally, the mesa structure (φ=20 μm) was formed by wet chemical etching.



(a) ADB-PD (b) REF-PD

Fig. 1. Schematic cross sections of the (a) UTC-PD with bonding interface, ADB-PD, and (b) reference sample without wafer-bonding, REF-PD.

3. Results and Discussion

The C-V characteristics of the fabricated PDs are shown in Fig. 2(a). The capacitance of ADB-PD is larger than that of the REF-PD in the bias range from 0 to 0.8 V. With an increase in bias voltage, it abruptly decreases, and when the bias exceeds 0.8 V, it becomes comparable to that of the REF-PD. This indicates that the REF-PD is completely depleted at 0 V, while the depletion in the ADB-PD starts around the bonding interface, and then the undoped layers begin to deplete at 0.8 V.

The I-V characteristics of the fabricated PDs were measured with a 0.1-mW 1.3-μm-wavelength optical input as shown in Fig. 2-(b). Photocurrents of 54 and 53 μA were observed at 0 V, and the corresponding sensitivities are 0.54 and 0.53 A/W for the ADB-PD and REF-PD, respectively. The equivalent photocurrent of the ADB-PD to that of REF-PD indicates successful minority-electron transport through the bonding interfaces under a static operating condition. Note that the photocurrent of the ADB-PD increases at bias voltage higher than 1 V, which seems to be caused by avalanche multiplication. The dark current of the ADB-PD rapidly increases from 0 V, and it shows a gradual increase at bias voltage higher than 0.8 V, while the dark current of the REF-PD remains over one order of magnitude smaller for the whole bias range. This drastic change in the dark current observed in the ADB-PD seems to be caused by tunneling due to an electric field concentrated in the bonding interface. The above considerations regarding the I-V characteristics are consistent with the aforementioned understanding of the specific behavior in the C-V characteristics.

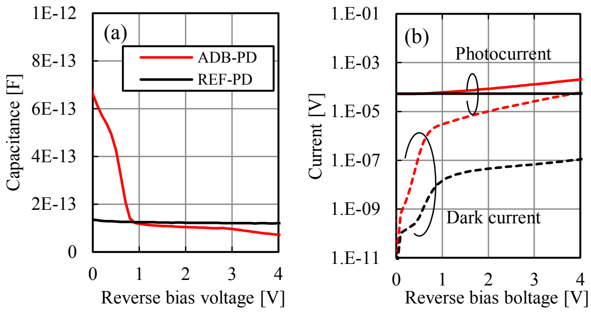


Fig. 2. (a) C-V and (b) I-V characteristics of the fabricated PDs.

Fig. 3-(a) and (b) show the frequency characteristics of the O/E response of the fabricated PDs at a reverse bias of 1 and 3 V. Here, the measured output power level at 50 MHz was defined as 0 dB for each device. The insets in Fig. 3 show electric field profiles of the ADB-PD estimated from the C-V profile.

At 1 V, the O/E response of the ADB-PD shows a rapid decrease up to about 5 GHz. Then, the ADB-PD shows similar roll-off to the REF-PD. This suggests the existence of electrons with a long time constant. The observed O/E response of the ADB-PD at 1 V is unexpected behavior when we look at the C-V characteristics and DC response in Fig. 2, because the ADB-PD is fully depleted. These results suggest that such an O/E response in the ADB-PD at 1 V is not due to the CR time constant limitation but to an intrinsic time delay of minority-electron transport. Possibly, the deteriorated intrinsic time delay is caused by some kind of traps for photo-generated electrons in the bonding interface, and it is expected to be improved when electrons become hot by increasing the electric field in the vicinity of the bonding interface. Fig. 3-(b) shows the O/E response of both PDs at 3 V. At the bias voltage of 3 V, the electric field in the vicinity of the bonding interface is clearly larger than that at 1 V as shown in the insets. As expected, when we look at Fig. 3-(b), the ADB-PD shows a similar O/E response to the REF-PD. These results indicate that there is little difference in the transport characteristics of minority electrons between the ADB-PD and REF-PD.

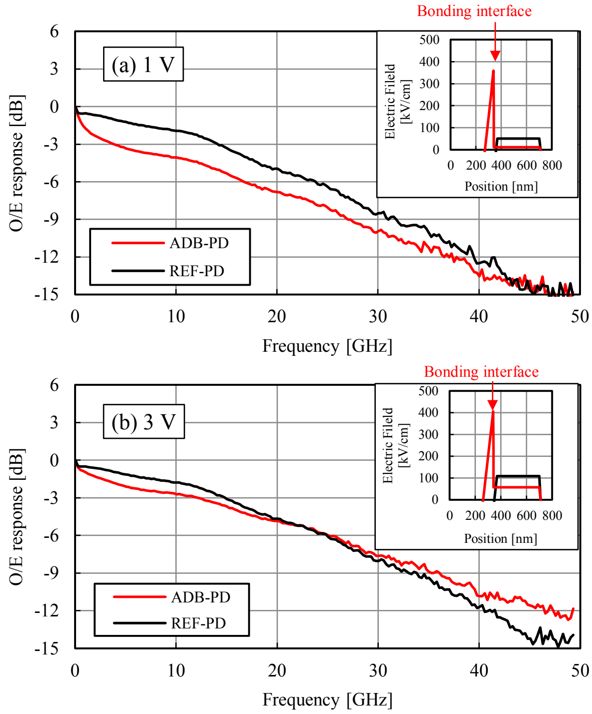


Fig. 3. O/E response at reverse bias voltages of (a) 1 and (b) 3 V. The insets are the electric field profiles calculated from C-V measurements.

4. Conclusions

We fabricated a UTC-PD with an InGaAs/a-Ge/InGaAs interface by wafer bonding and experimentally investigated minority-electron transport through the bonding interface from its C-V characteristics and DC- and O/E-response. It was found that an electric field concentrates in the vicinity of the bonding interface and that the obtained DC response is comparable with the reference PD. As for O/E response, the fabricated PD displayed deteriorated characteristics in the low-frequency domain. By increasing the bias voltage, or the electric field in the vicinity of the bonding interface, we obtained an equivalent O/E response to that of the reference PD. These results indicate that the minority hot electrons through the bonding interface show almost equivalent transport characteristics to those in the conventional epitaxially grown semiconductor structure.

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