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Realization of Large Breakdown Voltage of GaAsSb-Based Backward Diodes using Carrier Depletion Effect Originating from Nanowires

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Abstract

In this study, the forward breakdown voltage (BV) of GaAsSb-based backward diodes (BWDs) was significantly increased using a nanowire structure with thin AlOx passivation film. With device simulations, the mechanism of the increased BV originating from the carrier depletion brought by the nanowire size effect was clarified.

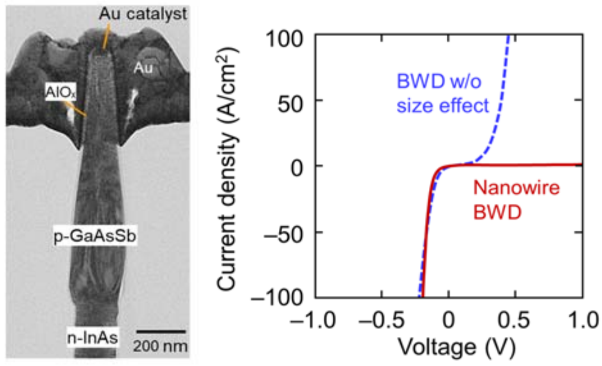
1. Introduction

Ambient RF energy harvesting is attractive for batteryless internet of things sensors because RF power can be obtained anywhere, such as base stations for cellphones or wireless local area networks. Schottky barrier diodes (SBDs) are used as RF-to-DC energy converters for ambient RF energy harvesting. However, the *I−V* characteristic of SBDs dominated by thermal carrier diffusion mechanism limits efficient power conversion, particularly under low microwave powers of less than 1 μW. Backward diodes (BWDs) utilizing interband tunneling are one of the candidates to improve power conversion in low RF power conditions. They have larger nonlinear characteristics than the conventional SBDs at around zero bias, which results in high sensitivity for low-power microwaves. We have reported that mesa BWD can harvest low-power microwaves [1]. However, the drawback using the conventional BWDs is the dynamic range. In [1], the input power was limited to lower than 0 dBm because of the small breakdown voltage (BV) of the BWDs (around 0.4 V). As a new type of BWDs, we have been developing nanowire BWD (NW BWD), which is expected to improve the performance of BWDs by applying size effect considering parameters such as capacitance. In this paper, we report our novel finding that the NW size effect drastically improves the BV of BWDs.

2. Experimental Results

Device Characteristics of Nanowire BWDs

Nanowire BWDs were developed using a type-II heterojunction of p-GaAsSb/n-InAs [2]. Figure 1(a) shows a cross-sectional structure of the fabricated NW BWD. The hetero NWs were grown using the position-controlled VLS growth method. The length and diameter of the NW are approximately 1.7 μm and 0.2 μm, respectively. The NW sidewall was passivated with a 14 nm AlO_x film by atomic layer deposition. An anode electrode was formed on the top of the nanowires, which consisted of a p^+-GaAsSb segment. The *I−V* characteristic of the NW BWD is shown in Fig. 1(b). As a comparison, an *I−V* curve of a typical mesa BWD with a size of 2.0 μm is displayed in the figure as a broken line [3]. The mesa BWD shows forward current above 0.4 V, which is dominated by the diffusion current of a p-n heterostructure. In contrast, it was found that the NW BWD significantly suppressed the forward current up to 1 V. The increased BV will improve the dynamic range of RF-to-DC power conversion. The mechanism of the BV improvement was investigated by a device simulator.



(a) (b)

Fig. 1 (a) Nanowire backward diode structure; (b) solid line: *I−V* characteristic of the NW BWD; broken line: curvature of typical BWDs without size effect.

Device Simulation of Nanowire Structures

We performed device simulations to clarify the reason the forward BV was increased in the NW BWD. In the simulation, a simplified structure without tunnel junction was employed because the tunnel junction is not effective at high-forward-bias condition. We thought that the increased BV was brought about by a particular electrode structure around the Ohmic

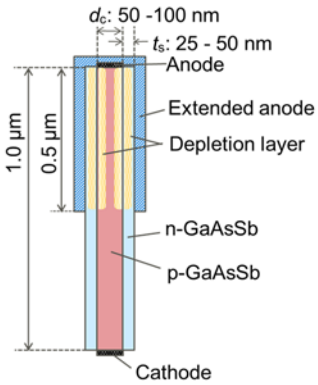


Fig. 2 A cross-sectional diagram of the structure without BWDs used for device simulations.

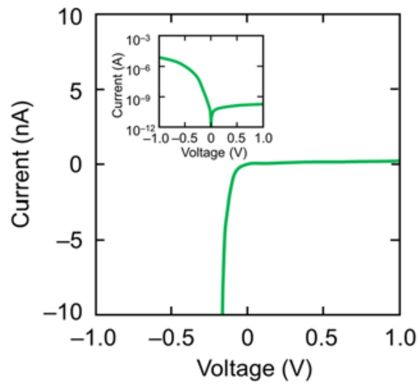


Fig. 3 Simulated linear $I-V$ characteristic of nanowire device with a core of 50 nm and shell of 25 nm. The inset shows a logarithmic current dependence.

region in the nanowire structure. Therefore, cylindrical nanowire structures consisting of a p-GaAsSb core and an n-GaAsSb shell were used as shown in Fig. 2. The n-GaAsSb shell can be used as a *virtual* passivation film with tunable dielectric properties. The nanowire length was set to 1.0 µm. The diameter of the p-GaAsSb (1×10^{18} cm^{-3}) core (d_c) was varied from 50 to 100 nm, while the thickness of the surrounding n-GaAsSb (1×10^{17} cm^{-3}) shell (t_s) was varied from 20 to 50 nm. Ohmic electrodes were set at both side of the nanowires. We introduced a 0.5 µm-length-extended electrode, which was connected to an anode metal, to represent the actual electrode configuration of the fabricated devices. The $I-V$ characteristic was simulated using ATLAS^{TM}, produced by Silvaco. When the p-GaAsSb core had a diameter, d_c, of 100 nm and n-GaAsSb shell thickness, t_s, of 50 nm, the nanowire displayed an Ohmic characteristic for both negative- and forward-bias directions, which means that no effect came from the *virtual* passivation film and the top electrode. In contrast, when both d_c and t_s were reduced to half (d_c: 50 nm, t_s: 25 nm), the characteristic completely changed, as shown in Fig. 3. A significant current suppression for the forward-bias condition was obtained even though the device had no tunnel junction between the anode and cathode electrodes. With the detailed investigations of the distribution of carrier density, we found that current suppression for the forward-bias condition originated from the nanowire shape effect and the device configuration. That is, in the case of d_c of 50 nm and t_s of 25 nm, the carriers in the p-GaAsSb core region close to the extended electrode was fully depleted when forward bias was applied. We believe that the same mechanism occurred for the fabricated NW BWD.

Mechanism of large BV in the Nanowire BWDs

From the simulated results above, we suggest the mechanism of the actual NW BWD we fabricated. In the calculation, a p/n nanowire core-shell structure was used. The actual NW BWD is different, but the metal-insulator-semiconductor (MIS) structure composed of a p-GaAsSb NW segment, thin 14 nm-thick AlO_x dielectric film, and Au-based top electrode is considered to act in a similar manner. The suggested mechanism of the large BV is depicted in Fig. 4. The important point is that the top of the NW has a small diameter that is

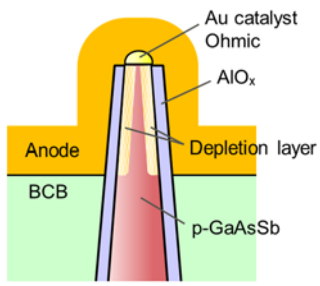


Fig. 4 Suggested mechanism of large BV in fabricated nanowire BWDs.

comparable to the diameter of the Au catalyst (40 nm), and the AlO_x entirely covered the sidewall of the p-GaAsSb segment. Such configuration can easily deplete the top of the p-GaAsSb segment with a small forward bias, resulting in current suppression. By applying this effect, the NW BWDs performance will be further improved with the separate design of tunnel current and BV.

3. Conclusions

We investigated a BWD with a large BV using a nanowire structure and clarified that the BV originated from the carrier depletion coming from the NW shape effect. The NW BWDs are promising to be developed as rectifiers with high sensitivity and a large dynamic range.

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