Statistics on Applied Voltages in Schottky Barrier Diodes at same Forward Current in a Fabrication Process

Kui Zhang, Hong-Dong Zhao, Hafiz Shehzad Ahmed, and Mei Sun

***Abstract*—A batch of Al/n-Si Schottky barrier diodes (SBDs) have been manufactured in the same fabrication process and the forward bias current–voltage (*I-V*) characteristics of SBDs in the same fabrication process are measured at 300K. After the forward-bias *I–V* characteristics of 1300 SBSs are measured, the statistics histogram on the applied voltages in 1300 SBDs are presented at forward bias currents of 1, 10, 50 and 150 mA, respectively. The applied voltage fluctuations of SBDs at the same forward bias current are given. The positive skewed distribution of the applied voltages at forward currents of 10, 50 and 150 mA are found, respectively, whereas the normal distribution of applied voltage at a forward bias current of 1 mA is given. It is also showed that not only the range of applied voltage is enlarged, but also the difference between the average voltage and the median applied voltage increased with the forward bias current. This may be due to the variation of series resistance in SBDs at high forward bias current levels.**

***Index Terms*—Schottky diodes, statistics, voltage, normal distributions**

I. Introduction

The SBD has advantages of higher response frequency than the p-n junction diodes, as the majority carriers can move rapidly in or out of the semiconductor to facilitate the variation in the depletion. The high-performance SBD is one of the most fundamental devices for their potential applications in rectifying junctions, sensors and etc [1], [2]. SBDs on Si, GaAs, GaN, SiC and diamond have been fabricated [3]-[13] to reduce the saturation current, modify the ideality factor and improve the breakdown voltage, in which various metals including Al, Cu, Cr, Ti and V are contacted with the semiconductor [3]-[5]. [7], [10]. It is often found that the *I-V* characteristics are measured in SBDs with a range of temperature and the thermionic emission (TE) model is usually adopted [3], [8], [10], [15], [16]. The capacitance–voltage and capacitance–conductance spectroscopy are also effective methods to determine the parameters of SBDs [12], [14]. As we known, although there are a vast number of reports on the characteristic parameters including barrier height, ideality factor and series resistance in SBDs, the investigation are usually obtained from a few SBDs. Moreover, such analyses performed in a few SBDs are insufficient to give the detailed information about a group of SBDs. To the best of our knowledge, very few experimental works have focused on investigation of the statistics on a large number of SBDs. The similar characteristics of SBDs in a fabrication process are usually assumed, and the model with normal distribution is widely adopted in the reliability analysis of a group semiconductor devices. In this paper, the statistics of SBDs are presented from the forward bias *I-V* characteristics in the experiment and skewed distributions of the applied voltages at high forward current levels are showed. The rest of the paper is organized as follows: Section II gives experimental procedure and theory of SBDs. Section III provides the statistics of SBDs and analyses. Section IVdraws conclusions of this paper.

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II. Experimental and Thoery

In this study, 5 μm-thick n-Si:P layer was grown on n-Si (111) substrate (thickness: 450 μm) with about 0.01 Ω·cm resistivity ($N_D \approx 4\times10^{18}$ cm^{-3}) and diameter of 4 in. by an ultra high vacuum chemical vapor deposition. The carrier concentration in the epilayer is about 1×10^{16} cm^{-3}. The native oxide layer on the front surface of the epilayer was removed in HF:H_2O (1:10) solution after the lithography process had been performed. The Schottky contacts were formed onto the front face of Si by the thermal evaporation of Al with radius of about 130 μm. The wafer was cut into pieces containing a single SBD by a diamond-edged saw. A 200 nm thick Al metal was also deposited over the entire back of devices as an ohmic contact. These contacts were deposited under vacuum with a pressure below 10^{-6} Torr. In order to get low resistivity ohmic contact, wafer was annealed at about 500 ^{0}C for 5 min in N_2 atmosphere. The forward bias *I–V* characteristics of SBDs were measured at room temperature on a semiconductor parameter analyzer.

According to the thermionic emission theory in the presence of the series resistance, the forward bias *I–V* characteristic of a SBD is given [2], [3], [8]:

$$I = I_S\left[\exp\left(\frac{V - IR_S}{\eta kT/q}\right) - 1\right] \quad (1)$$

where η is the ideality factor, q is the elementary charge, R_S is the series resistance, T is the absolute temperature, k is the Boltzmann constant and I_S is the reverse saturation current, which is given by

$$I_S = AA^*T^2 \exp\left(-\frac{q\Phi_B}{kT}\right) \quad (2)$$

where A is the diode area, Φ_B is the Schottky barrier height, A^* is the effective Richardson constant.

III. Result and Discussion

We have made a batch of SBDs in a fabrication process, in which the forward current of 160 mA can transport across the metal–semiconductor interface at the applied voltage of 1.3 V. The forward bias *I–V* characteristics of 100 BSDs at 300 K are plotted in Fig. 1. The behaviors of the curves show that the forward current will increase exponentially with the applied voltage, as described in Eq. 1. The forward current *I* is about 1 mA at the applied voltage *V*=0.6 V in SBDs, all the curses are mixed together. The diversity of forward bias *I–V* characteristics will be presented distinctly with increasing the applied voltage. The forward currents *I* are greater than 120 mA in the most of SBDs at the applied voltage *V*=1.0 V, however, the forward currents *I* of a few SBDs are less than 100 mA.

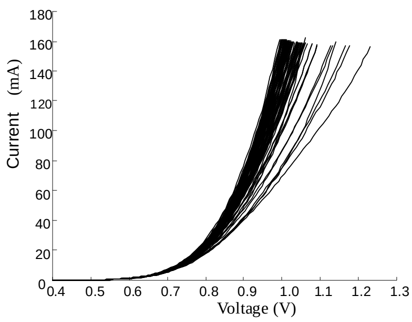

Fig. 1. Measured forward bias *I* – *V* characteristics of 100 SBDs at 300 K

1300 Al/n-Si SBDs fabricated in one processing batch are investigated their *I* – *V* characteristics at room temperature. We keep the same conditions of semiconductor technology such as the temperature, time and doping concentrations during the formation of semiconductor devices. It is noted that the values of applied voltage in 1300 SBDs are plotted at the forward currents of 1, 10, 50 and 150 mA, respectively. The applied voltages of SBDs are different at the same forward current even if the SBDs are identically prepared on a sample. In order to describe the abnormal behavior in Fig. 1, the histograms of the applied voltage in 1300 SBDs are plotted at the forward currents of 1, 10, 50 and 150 mA in Fig. 2, respectively, and the applied voltage fluctuations of SBDs at the same forward bias current are found. The average voltage, median applied voltage and standard deviation of the applied voltage at the same forward currents *I*=1, 10, 50 and 150 mA, respectively, are given in Table 1.

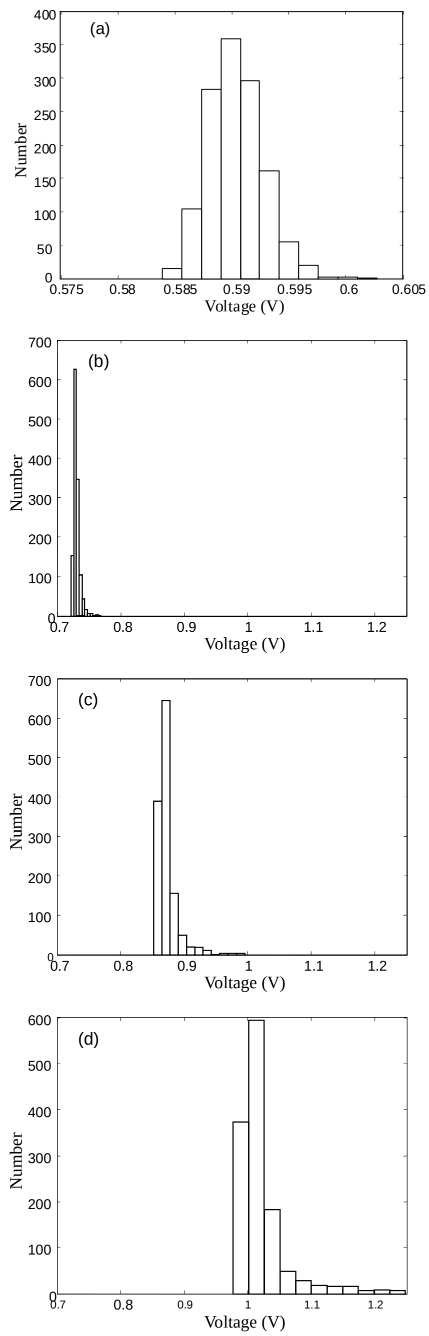

Fig. 2. Histogram of the applied voltages in 1300 SBDs at the forward current (a) *I*=1 mA, (b) *I*=10 mA, (c) *I*=50 mA, (d) *I*=150 mA.

TABLE I
THE AVERAG VOLTAGE(V_A), MEDIAN APPLIED VOLTAGE(V_M), STANDARD DEVIATION OF APPLIED VOLTAGE (ΔV) AT THE SAME FORWARD CURRENTS

I (mA)	1	10	50	150
V_A (V)	0.5904	0.7305	0.8734	1.0221
V_M (V)	0.5902	0.7296	0.8690	1.0090
ΔV (V)	0.0025	0.0049	0.0161	0.0395

The normal distribution is given as the histogram described in Fig. 2(a), which is widely adopted in the reliability analysis of a group semiconductor devices. However, it is found that the applied voltages follow a 'heavy-tailed and skewed' probability distribution with the increasing of the forward current in Fig. 2(b), (c), and (d), in which traditional normal distribution may not be proper. The applied voltage of about 0.7282 V is needed for the most of SBDs at the forward current I=10 mA, but the higher voltage is applied to a few SBDs at same forward current in Fig. 2(b). The histogram will be extended to the large applied voltage and the prolongation range of the applied voltage is improved with the forward current. In order to present the skewed normal histogram, the average voltage and median applied voltage versus the forward current are plotted in Fig. 3. As can be seen, the normal histogram is given as average voltage is nearly equal to median applied voltage in low forward current, but the positive skewed distribution is showed at the high forward current due to the fact that median applied voltage is smaller than the average voltage.

According to the spatial inhomogeneities of gas and temperature in the substrate during the fabrication process of SBDs, the carrier density in the epilayer and the ohmic contact from the metal-semiconductor interface let the series resistance to fluctuate. The series resistance plays a significant role at the high forward current, and the high applied voltage is necessary to achieve the same forward current. The series resistance fluctuations result in the positive skewed distribution of the applied voltage at the high forward current.

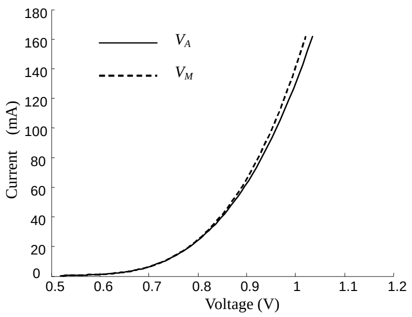

Fig. 3. The average voltage (V_A) and median applied voltage (V_M) versus the forward current.

IV. Conclusion

The statistics of experimental investigation on the applied voltages of 1300 BSDs are presented in the paper. After the measurement of forward bias *I-V* characteristics of 1300 SBDs, the histograms of the applied voltage in SBDs are given at the different forward current in a fabrication process of semiconductor devices. The normal distribution of the applied voltage is given at the forward current I=1 mA, in which the standard deviation of the applied voltage is 0.0025 V. The average value and standard deviation of the applied voltage increase with the forward current. The skewed distributions of the applied voltages in 1300 SBDs are firstly reported, which can be only measured at the high forward current in a large number of SBDs, due to the series resistance. The normal distribution of the applied voltage in SBDs can only fit to the low forward current. The applied voltages with similar values are necessary most of SBDs at the high forward current, except a few SBDs with the high applied voltages. These experimental results are likely to be important for the application of SBDs

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