Hole Schottky barrier height enhancement and its application to metal–semiconductor–metal photodetectors

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Hole Schottky barrier height enhancement and its application to metal–semiconductor–metal photodetectors

S. D. Lin and C. P. Lee[a)]
Department of Electronics Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan, Republic of China

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Hole Schottky barrier heights on GaAs have been studied experimentally by using a conventional metal–semiconductor–metal photodetector (MSMPD) structure. The Schottky barrier height for holes was obtained directly by the hole-current dominated dark current measurement of the MSMPD. With a thin, highly doped surface layer, control of the Schottky barrier heights for holes from 0.48 to 0.79 eV was obtained. By using these engineered Schottky contacts in the MSMPDs, over three orders of magnitude reduction in the dark currents of the MSMPDs was achieved.
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I. INTRODUCTION

It is well known that the Schottky barrier height in many semiconductors is relatively insensitive to the metal used because of the pinning of the Fermi surface level. This is particularly true for GaAs.[1–3] The Schottky barrier height is an important parameter for many devices, such as field-effect transistors (FET), high-mobility electron transistors (HEMT), and metal–semiconductor–metal photodetectors (MSMPDs). Adjusting the barrier height to a desirable value can lead to the improvement of device performance. Among various methods to control the Schottky barrier heights,[4–11] using a thin, highly doped interfacial layer is most effective and has been used for a long time. In 1974, Shannon showed that the Schottky barrier heights for electrons and for holes on silicon could be controlled by ion-implanted layers.[8] Following that work, the method was applied to other semiconductors, e.g., GaAs,[2,9] InP,[10] and InGaAs.[11] A thin surface epilayer has also been used to modify the Schottky barrier heights. However, most of these investigations have been focused on the Schottky barrier height for electrons (ϕ_{bn}) only, and the studies of Schottky barrier height for holes (ϕ_{bp}) are relatively few. Among the reported results on hole Schottky barrier heights, the modification was achieved by introducing an additional layer (e.g., metal, semiconductor, or insulator).[4–7] The modified hole Schottky barrier heights were measured by using p-type GaAs on a p^+-GaAs substrate. Results showed that the barrier heights can be controlled in the range of 0.4–0.9 eV and the sums of the electron and hole Schottky barrier heights are equal to or less than the GaAs band-gap energy.

In a conventional, unmodified Schottky diode, the sum of the electron and the hole Schottky barrier heights is equal to the energy gap of the semiconductor.[3] That is,

$$\phi_{bn}+\phi_{bp}=E_g . \tag{1}$$

This relation has been proven by experiments on many kinds of semiconductors.[1,12] From Eq. (1) one can easily determine the hole Schottky barrier height once the electron Schottky barrier height is known. This is why there is no need to study the hole Schottky barrier height directly. However, for the modified Schottky diode with a thin, highly doped layer, the equality may not be correct anymore. In the following, the reason is explained by an example of an n-type Schottky diode with a thin p^+ layer between the metal and the semiconductor. Assuming that the doping concentrations of the n-type semiconductor and the thin p^+ layer are N_D and N_A, respectively, and d is the thickness of the p^+ layer, according to the depletion model, the enhancement of the electron Schottky barrier height ($\Delta\phi_{bn}$) is

$$\Delta\phi_{bn}=\frac{qN_A}{2\varepsilon_s}d^2, \tag{2}$$

where q is the unit electron charge, and ε_s is the dielectric constant of the semiconductor.[3,8] On the other hand, the reduction of the hole Schottky barrier height consists of two major contributions. The first, indicated by $\Delta\phi_{bp1}$, is caused by image force lowering due to an enhanced electric field at the interface. It can be estimated by the formula below[3]

$$\Delta\phi_{bp1}=\frac{q}{\varepsilon_s}\sqrt{\frac{N_A d}{4\pi}}. \tag{3}$$

The other one is the enhancement of the tunneling current of holes. By the calculation of Shannon in 1974,[8] the amount of reduction will be significant if the electric field at the interface is larger than about 10^5 V/cm, i.e., $N_A d > 10^{12}$ cm^{-2}. The quantity of the reduction of the hole Schottky barrier height contributed from the tunneling current depends on the hole's effective mass and the surface electric field, etc., so the equality in Eq. (1) obviously fails. In general, the summation of the electron and the hole Schottky barrier heights is larger than the energy gap of the semiconductor. That is why the direct measurement of hole Schottky barrier height is necessary in these modified Schottky diodes.

In the present article, we investigated the hole Schottky barrier height on GaAs by using a conventional metal–semiconductor–metal (MSM) photodetector structure. The

[a)]Electronic mail: cplee@cc.nctu.edu.tw

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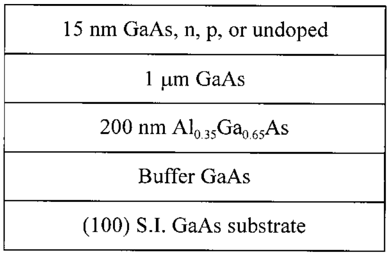

FIG. 1. A schematic diagram of the layer structures of samples N_1 ($N_D = 5\times10^{17}$ cm^{-3}), N_2 ($N_D=1\times10^{18}$ cm^{-3}), N_3 ($N_D=2\times10^{18}$ cm^{-3}), P($N_A=1\times10^{18}$ cm^{-3}), and U (undoped) used in the study.

structure consists of two back-to-back Schottky diodes. Ignoring the two-dimensional and the image force lowering effects, under the flatband condition, i.e., the semiconductor between two metal contacts totally depleted, the total current J_t through the structure can be describe approximately by the simple relation:

$$J_t = J_n + J_p = A_n^* T^2 e^{-q\phi_{bn}/kT} + A_p^* T^2 e^{-q\phi_{bp}/kT}, \quad (4)$$

where $J_n(J_p)$ is the electron (hole) current injecting from the cathode (anode), and $A_n^*(A_p^*)$ is the Richardson's constant of the electron (hole).[13] For GaAs, the Richardson's constant of electrons is about an order smaller than that of the holes.[3] Therefore the hole current J_p will be dominant if ϕ_{bp} is equal or less than ϕ_{bn}. In this case the hole Schottky barrier height ϕ_{bp} can be obtained from the dark current measurement of the MSM photodetector. In addition, we also studied the modified Schottky contacts containing a thin, highly doped GaAs layer by the same structure. For a 15 nm, 2×10^{18} cm^{-3} Si-doped layer, a reduction of over three orders of magnitude for the dark current for the MSM photodetector was achieved.

II. EXPERIMENT

A. Sample growth and device fabrication

The samples used for this study were grown by molecular beam epitaxy using a Varian GEN II system. The sample structure is schematically shown in Fig. 1. The structure consists of, starting from the (100) semi-insulating GaAs substrate and the GaAs buffer layer, a 200 nm $Al_{0.35}Ga_{0.65}As$ layer, a 1 μm GaAs layer, and a 15 nm GaAs layer. All layers except the top 15 nm of GaAs were undoped. Five samples (N_1, N_2, N_3, P, and U) with the same structure were grown to study the doping effect of the top layer. Samples N_1, N_2, and N_3 were Si-doped with concentrations of 5×10^{17}, 1×10^{18}, and 2×10^{18} cm^{-3}, respectively. Sample P was Be-doped with a concentration of 1×10^{18} cm^{-3}, and for comparison sample U had an undoped top layer. In order to minimize the effect of the dopant diffusion during growth, the substrate temperature was decreased from the normal growth temperature of 575 °C to about 540 °C before the top layer growth. In fact, the structure of sample U is exactly the same as a conventional MSMPD.[14] In the structure, the undoped GaAs layer is the absorption layer, and the AlGaAs layer is the absorption stop layer, to prevent the photogenerated carriers in the substrate from being collected by the electrodes of the photodetector. Besides, because the characteristics of Schottky contacts are very sensitive to the process procedures, a sample with the structure of a conventional Schottky diode was grown on (100) n^+-GaAs substrate. This sample served to monitor the process conditions of other samples.

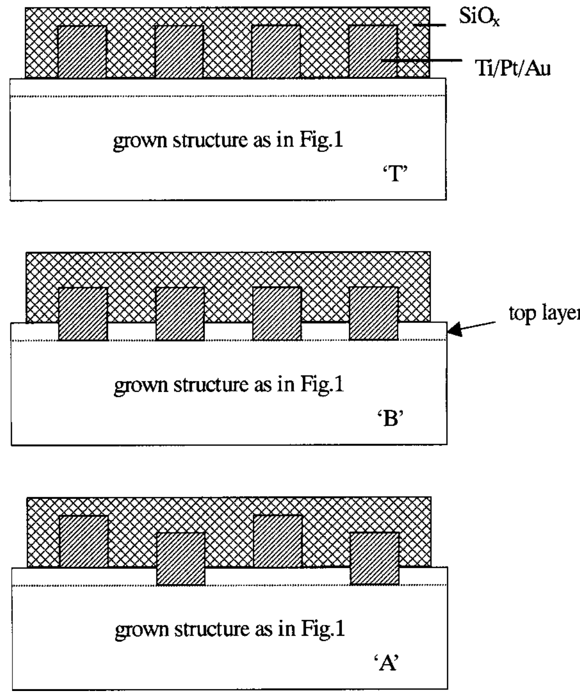

FIG. 2. A schematic diagram of the three kinds of devices: T, B, and A.

All five samples were processed together. The process was basically the same as that of the conventional MSMPDs, i.e., it was composed of three main steps: finger metallization, dielectric passivation and isolation, and pad formation. Three different devices were fabricated on each sample. They consist of conventional MSMPDs with both electrodes on the top layer, MSMPDs with one electrode on the top layer and the other on the absorption layer, i.e., the surface on which the top layer was etched off, and MSMPDs with both electrodes on the absorption layer. In this study they are called T (top), A (asymmetry), and B (bottom) devices, respectively. A schematic of the three devices is shown in Fig. 2. The Schottky metal used was Ti/Pt/Au, with a thickness of 30 nm/30 nm/100 nm. Before the top metal deposition, the samples were treated with an UV/ozone stripper, and then dipped in HCl/H_2O (1:1) for 30 s to remove surface contaminants and native oxide. After both finger electrodes were formed, a surface passivation layer of 150 nm silicon-oxide (SiO_x) was deposited using plasma-enhanced chemical vapor deposition (PECVD). In the finished devices, the finger spacing was 6 μm and the active area was 200×200 μm^2.

During the device processing, the conventional Schottky diodes were fabricated at the same time. Two diodes were prepared, one with the Schottky metal on the as-grown surface (denoted as S_T), and the other with the schottky metal on an etched surface (denoted as S_B).

B. Result and discussion

The current–voltage characteristics of all devices were measured with a HP4145 semiconductor parameter analyzer

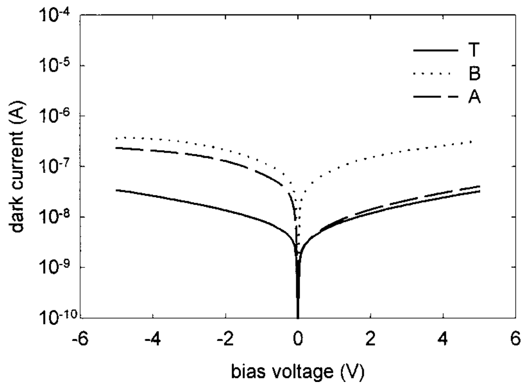

FIG. 3. The measured current–voltage characteristics of the devices T, B, and A of sample N_2.

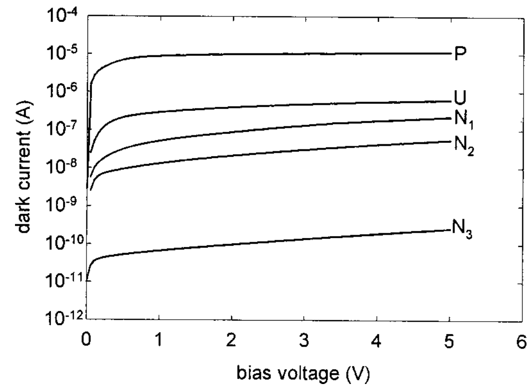

FIG. 4. The measured current–voltage characteristics of the T devices of all the samples: P, U, N_1, N_2, and N_3.

on a probe station. The conventional Schottky diodes S_T and S_B were measured first. The obtained ideality factors and electron Schottky barrier heights for devices $S_T(S_B)$ were 1.03 (1.04) and 0.85 eV (0.86 eV), respectively. From these results we can conclude that first, the Schottky contacts formed by our process procedure were pretty good, and second, the Ti/Pt/Au–GaAs Schottky contacts on the as-grown surface and the etched surface had almost the same electrical characteristics.

In the following, the current–voltage characteristics of the MSM devices were measured under the dark condition. For sample U, the *I–V* curves of the devices T, A, and B were almost the same. This is because the Schottky contacts of both electrodes were formed on the undoped GaAs surface. However, for other samples, since the Schottky contacts of devices T, A, and B were formed on the layers with different doping, the *I–V* curves were totally different. For example, the *I–V* curves of the various device types of sample N_2 were shown in the Fig. 3. Devices T and B had nearly symmetric *I–V* curves while device A showed an asymmetric *I–V* curve. The cause for such a difference is the location of the electrodes. For devices T and B, both the anode and the cathode were on the same layer but for device A, one electrode was on the n^+ layer while the other was on the undoped GaAs layer. It should be noted that under positive bias voltage the electrons injected from the bottom electrode. Comparing the *I–V* curves of these devices, we found that, for positive bias, the *I–V* curves of devices A and T are almost the same. On the other and, for negative bias, the *I–V* curves of devices A and B are almost the same. This result can be understood by the following explanation. The *I–V* characteristics of MSMPDs can be approximately described by Eq. (4) mentioned before. However, the Schottky barrier heights for electrons and for holes (ϕ_{bn} and ϕ_{bp}, respectively), were modified. Since the top layer of sample N_2 was *n* typed, ϕ_{bn} was reduced and ϕ_{bp} was enhanced. If the amount of change in ϕ_{bn} and ϕ_{bp} are $\Delta\phi_{bn}$ and $\Delta\phi_{bp}$, respectively, the dark currents of the devices T and B of this sample can be estimated by the following equations

$$J_{tT}=J_{nT}+J_{pT}=A_n^*T^2e^{-q(\phi_{bn}-\Delta\phi_{bn})/kT}+A_p^*T^2e^{-q(\phi_{bp}+\Delta\phi_{bp})/kT}, \quad (5)$$

$$J_{tB}=J_{nB}+J_{pB}=A_n^*T^2e^{-q\phi_{bn}/kT}+A_p^*T^2e^{-q\phi_{bp}/kT}, \quad (6)$$

and, for device A, due to the asymmetric structure, the dark current of the device under different polarity has to be estimated with different equations as shown below

$$J_{tA}^+=J_{nA}^++J_{pA}^+=A_n^*T^2e^{-q\phi_{bn}/kT}+A_p^*T^2e^{-q(\phi_{bp}+\Delta\phi_{bp})/kT}, \quad (7)$$

$$J_{tA}^-=J_{nA}^-+J_{pA}^-=A_n^*T^2e^{-q(\phi_{bn}-\Delta\phi_{bn})/kT}+A_p^*T^2e^{-q\phi_{bp}/kT}. \quad (8)$$

For unmodified Ti/Pt/Au–GaAs Schottky contacts, the barrier height, ϕ_{bn}, for electrons was about 0.85 eV, which is much larger than the hole's barrier height. So, the contribution of the electron current to the total current is negligible for MSM structures. If we neglect all electron current in the above equations, we can easily see that $J_{tT}=J_{tA}^+$ and $J_{tB}=J_{tA}^-$. So, from the *I–V* curve in Fig. 3, we can conclude that the hole current dominants in all devices for sample N_2. Even with the modified Schottky barrier height, the electron barrier height is still larger than the hole barrier height. In fact, for all the samples (N_1,N_3, and P), the total currents of all devices were dominated by the hole currents, as observed by the equalities of $J_{tT}=J_{tA}^+$ and $J_{tB}=J_{tA}^-$ in the measured *I–V* curves.

As discussed in the Introduction, if the total current of the MSMPD is dominated by the hole current, we can determine the Schottky barrier height for boles with the total current easily. The *I–V* curves of devices T of all five samples are shown in Fig. 4. In the figure we can observe that the current increases slowly with the voltage for all the devices due to the increased image force lowering. From the *I–V* curves we can extrapolate the total current at zero voltage and then calculate the hole Schottky barrier heights. The Richardson's constant of holes used in the calculation was 74.4 $A/cm^2/K^2$. In Fig. 5 the calculated result is shown. First, it should be noted that the Schottky barrier height for holes of sample U is about 0.57 eV. The summation of this value and the Schottky barrier height for electrons (0.85 eV) is equal to the energy gap of GaAs exactly. This result is not surprising because sample U has an undoped top layer. The Schottky barrier is not modified so the result is consistent

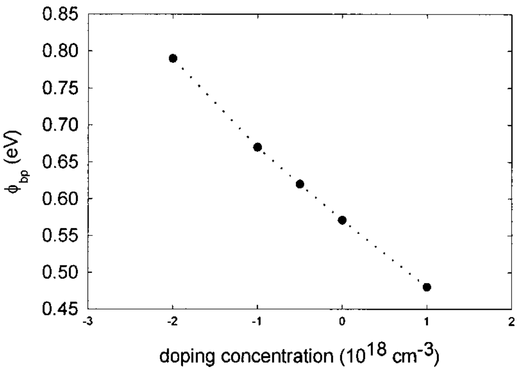

FIG. 5. The calculated Schottky barrier heights for holes from the result of Fig. 4, where in the axis for doping concentration, the positive side is *p* type, the negative side is *n* type, and the zero point is undoped.

with Eq. (1). This result also indicates the validity of this method for determining the hole Schottky barrier height.

Figure 5 shows that the determined Schottky barrier heights for holes in the range from 0.48 to 0.79 eV were obtained from different samples. Depending on the types of dopants and their doping concentrations, the barrier height can be varied from 0.48 to 0.79 eV. The largest barrier height was obtained when the top layer was *n* type with a doping concentration of 2×10^{18} cm^{-3}. When the top layer was P type with a doping level of 1×10^{18} cm^{-3}, the barrier height was reduced to 0.48 eV. As shown in the figure, the dependence of the barrier height on doping level is nearly linear. The tunable range of the holes Schottky barrier height is comparable to previous reported results and easier to implement due to its good linearity.[4–7] Because the hole barrier height can be greatly increased by the use of a thin n^+ top layer, the dark current of a MSMPD can be greatly reduced with such a structure. As shown in Fig. 4, the dark current measured from the MSMPD in sample N_3 (top layer with a N-type doping of 2×10^{18} cm^{-3}) is about three orders of magnitude lower than that measured from the detector on sample U (the conventional structure).

Finally, the responsivities of the devices of all the samples were measured using a commercial 0.85 μm laser diode pigtailed with a bare fiber. At an incident power of 25 μW, the measured responsivities of all T devices of samples N_1, N_2, N_3, and U were about 0.12–0.14 A/W under the bias voltage of 5 V. From this result we can conclude that the *n*-type doped top layer, which greatly suppress the dark current, does not degrade the responsivity of the devices. The internal quantum efficiencies of the devices were calculated by considering the thickness of the absorption layer, the reflection from the device surface, and the area of the fingers on the surface. The values were all around 80%.[14]

III. CONCLUSION

In conclusion we have used the structure of MSMPDs to investigate the modified and unmodified Schottky barrier heights for holes on GaAs. By using a thin and doped top layer, the barrier height can be varied over a wide range. From 1×10^{18} cm^{-3} P-type doping to 2×10^{18} cm^{-3} *n*-type doping the hole barrier height is changed from 0.48 to 0.79 eV. By using the modified barrier height of 0.79 eV we have obtained a reduction in the dark current for over three orders of magnitude for MSM photodetectors.

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