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Barrier height adjustment of Schottky barrier diodes using a double-metal structure

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ABSTRACT

The design and fabrication of double-metal (DM) Schottky barrier diodes with various Ti/Au area ratios and a polysilicon (poly-Si) guard ring structure are presented. A method that uses ion implantation in a poly-Si film for guard ring fabrication is used to prevent damaging the silicon surface. Experimental results of the Ti/Au DM structure and the relationship between the effective barrier height and the area ratio are presented and discussed. It was found that the effective barrier height of the Schottky barrier diode can be adjusted by changing the ratio of the DM area, which is not possible with a single-metal structure.

1. Introduction

Schottky barrier diodes (SBDs) with a low forward voltage drop (V_F), a low reverse leakage current density (J_R), low power dissipation, and a high breakdown voltage (V_{BD}) are urgently required in the electronics industry [1–4]. V_F and J_R, which strongly depend on the Schottky barrier height (SBH, defined as ϕ_{bn}), are key factors in determining the power dissipation of SBDs for power applications. In general, J_R decreases and V_F increases with increasing SBH [5–7]. Resolving the trade-off between V_F and J_R, obtaining the theoretical breakdown voltage in actual SBDs, and minimizing the power dissipation of SBDs without sacrificing other device properties are still open problems in SBD fabrication.

In general, there is a trade-off between the forward voltage drop and the reverse leakage current in the design of conventional SBDs. To achieve an optimum SBH for SBDs that leads to minimum power dissipation, both a low forward voltage and a low reverse leakage current must be obtained; however, it is very difficult to achieve this for conventional one-metal Schottky diodes, because the effective SBH of SBDs cannot be well controlled to obtain low power dissipation. A high-barrier-height metal incorporated in a low-barrier-height metal on a Si epi-wafer to form a SBD has been proposed to solve this issue. The forward voltage is decreased because the forward current flows through a low-ϕ_{bn} Schottky-metal contact and the reverse current is decreased because the high-ϕ_{bn}Schottky-metal contact results in a depletion region where pinch-off occurs [5–9].

Theoretical and experimental studies on the optimum device design and device fabrication process are conducted in this work. The influence of structural parameters, the type of Schottky metal, and the area ratio between the two Schottky metals used in the device are investigated in detail. The physics of the operation of a Schottky barrier rectifier is first discussed with an emphasis on the characteristics of devices suitable for power switching applications. It was found that the Schottky barrier height strongly depends on the double-metal (DM) area ratio. An optimal barrier height, which minimizes power dissipation, was obtained. In addition, the double Schottky-metal structures discussed in this work were fabricated to make rectifiers with a low barrier height, which resulted in major reductions in the forward voltage drop and the power dissipation of the SBD [10,11].

2. Experimental procedure

The epi-wafers used in experiments were n^-(20 μm)/n^+ Si epi-wafers with the (111) orientation. The n^-epitaxial layer had a resistivity of 10 Ω cm, and the n^+ substrate had a resistivity of 0.01 Ω cm. To obtain an optimal Schottky barrier height, a combination of high- and low-barrier-height metals, as shown in Fig. 1, was used [11]. Evaporation is particularly suited for the fabrication of such DM structures. Note that various DM ratios of Ti/Au and Al were used to form the Schottky and backside ohmic contacts, respectively. All SBDs had an active region area of 0.01 cm^2 and a field plate width of 30 μm. The width of the Ag metal was set to 3 μm. The width of the polysilicon (poly-Si) guard ring was 30 μm. The poly-Si guard ring was used to prevent the edge breakdown effect and surface leakage [2–5]. To adjust the barrier height of the Schottky contact, a DM Ti/Au structure was used for the fabrication and simulation.

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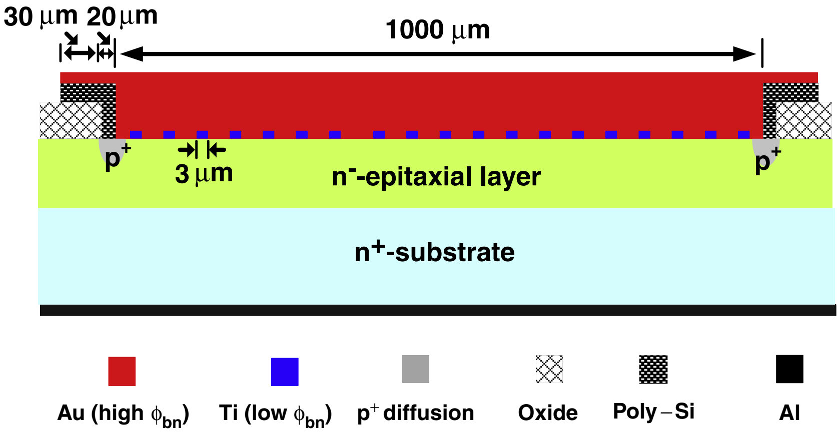

Fig. 1. Schematic diagram of proposed SBD with double-metal structure.

The basic fabrication process of SBDs used in our work is illustrated in Fig. 2. The wafer was first cleaned with a standard RCA process, and then a 0.5-μm-thick SiO_2 layer was grown at 1100 °C with wet oxidization. Oxide etching was then used to define the guard-ring pattern (Fig. 2(a)). An un-doped poly-Si film with a thickness of approximately 300 nm was then deposited using a low-pressure chemical vapor deposition reactor at 625 °C [4,5]. The poly-Si film was then subjected to BF_2^+ implantation at 120 keV with a dosage of 1×10^{16} cm^{-2} (Fig. 2(b)). After implantation, the sample was annealed at 950 °C in N_2 ambient for 20 min. The doped poly-Si over the guard ring region served as a dopant diffusion source for the guard ring. Poly-Si and SiO_2 etching, using $HNO_3 + HF + CH_3COOH$ mixed solutions and BOE (buffer oxide etcher) solution, respectively, were then conducted to open the silicon surface for Schottky metal deposition (Fig. 2(c)). Boron was then diffused into the poly-Si window to form a p^+-poly-Si guard-ring with a junction depth of about 0.24 μm [3–5,11]. This method, which uses ion implantation in a poly-Si film for guard ring fabrication, is used to prevent damaging the silicon surface.

A Schottky metal was deposited using an e-beam system under a pressure of around 2.67×10^{-4} Pa with a deposition rate of about 5 Å/s. A 500-Å-thick layer of a low-barrier-height metal, Ti, was evaporated onto the window to form the Schottky contact, and then the contact pattern was defined using photolithography (Fig. 2(d)). A 2000-Å-thick layer of a high-barrier-height metal, Au, was evaporated onto the contact window, and the Schottky contact region was defined. All SBDs had the same active region area of 0.01 cm^2 and the same field plate width of 30 μm. The width of the poly-Si guard ring was 20 μm. The width of the Ti layer was set to 3 μm. An alloyed Al (with 1% Si) ohmic contact was made on the backside of the proposed sample (Fig. 2(e)). Finally, all the samples were sequentially sintered at 400 °C for 30 min in N_2 gas and the device patterns were defined. With such a device design, the DM was connected to the p^+-poly-Si guarding ring, as confirmed from the ISE-TCAD simulator. A semiconductor parameter analyzer (HP-4145B) and a source-measure unit (SMU, Keithley 237) were used to measure the current–voltage characteristics. A capacitance–voltage (C–V) analyzer (Keithley 590) was used to measure the C–V characteristics of the fabricated SBDs. The junction depth of boron ions was analyzed using the spreading resistance profiling technique.

3. Results and discussion

In this section, the experimental results of the fabricated SBDs are presented and discussed with an emphasis on the characteristics for power switching applications. The modeling results of current flow path, measured current–voltage (J–V) characteristics, and effective barrier height are presented. The effects of the double metal area and the p^+-poly-Si guard structure of SBDs on the blocking capability of the device are also investigated.

3.1. Current flow paths of SBDs

Fig. 3(a) and Fig. 3(b) show the current flow paths for a forward bias of 0.6 V and the depletion profile of various reverse biases, respectively. The Ti/Au area ratio was 0.23. The forward current paths are basically concentrated at the low-ϕ_{bn} Schottky Ti metal. The low-barrier-height-metal grid is designed so that the depletion layers will intersect under the Schottky barrier when the reverse bias exceeds a few volts. The forward voltage is decreased because the forward current flows through the low-barrier-height metal contact, and the reverse current is decreased because the high-barrier-height metal contact results in a depletion region where pinch-off occurs. That is the device contains multiple conductive channels under the Schottky barrier through which the current can flow into low-ϕ_{bn}Schottky Ti metal during forward biased operation. Under the reverse bias, the depletion layers formed at high-ϕ_{bn} Schottky Au contact junction spread into the channel. When reverse bias exceeds a few volts, the reverse current paths are pinched off by the depletion region, which suppresses the reverse current density of the SBD. The voltage of pinched off occurrence is dependent upon the Ti/Au area ratio. After the depletion layer pinch-off, the depletion region of high-ϕ_{bn}Schottky Au metal has completely filled the channel region, and a net charge is effectively reduced in the channel. Once this effect is formed, a further increase in the applied voltage is supported by it with the depletion layer extending toward the n^+ substrate; the pinch-off phenomenon shields the low-ϕ_{bn}Ti Schottky barrier from the applied voltage. This shielding prevents the Schottky barrier from lowering and eliminates the large increase in leakage current observed for conventional Schottky rectifiers. This can be apparent by the data shown in Fig. 4 of next section, where J–V curve, which is a main factor in determining leakage current and breakdown voltage, is plotted.

3.2. J–V characteristics of SBDs

The measured forward J–V characteristics of the double-Schottky-metal samples as a function of the area ratio of Ti/Au in the range of 0 to ∞, which is of interest for power rectifiers, are presented in Fig. 4. Note that the modified Norde method [10] was employed for the extraction of ϕ_{bn} and ideality factor. It should be noted that the reverse saturation and forward currents are a strong function of the