

Low Turn-On Voltage Schottky Diode in InGaP/GaAs HBT/BiFET Processes

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Abstract

In today's complex circuits used in wireless applications, multiple turn-on voltage diodes are desired for added design flexibility. In this work we report a novel Schottky diode with a lowered barrier height and turn-on voltage of 0.42 V in InGaP/GaAs HBT/BiFET processes based on the use of TaN as the anode material.

INTRODUCTION

InGaP/GaAs heterojunction bipolar transistors (HBT) and bipolar field effect transistor processes are widely used for wireless applications since they offer excellent features such as high power density and high efficiency. In typical InGaP/GaAs HBT/BiFET processes, the Schottky diode turn-on voltage is approximately 0.7V. Given the complexity of today's circuits used in wireless applications, a lower turn-on voltage diode is desired, in addition to the regular Schottky device, for added design flexibility.

In GaAs processes, a typical Schottky device is formed by placing the first metal interconnect layer or the FET gate metal layer directly on an n-doped GaAs layer. Given the work functions of the metals used in GaAs processes such as Au, Pt, W, Ni, and Ti, the resulting Schottky barrier height may be between 0.7V and 1V [1]. Skyworks' current InGaP/GaAs processes use a Ti/Pt/Au stack for the first metal interconnect which results in a Schottky diode with a barrier height of 0.8V and a turn-on voltage of 0.7V at a current density of $10 \mu\text{A}/\mu\text{m}^2$.

To provide enhanced functionality to today's circuits used in a wireless application in addition to other applications such as diode voltage drops, detectors, and mixers, a lower turn-on voltage is desirable. Typically, a lower turn-on Schottky diode can be configured as a planar doped barrier diode detector [2]. However, such a design involves materials generally not compatible with the fabrication of HBTs. Similarly, barrier-lowering schemes which involve the growth of a thin layer of opposite doping polarity are also generally not compatible with HBT processes.

In this work, we propose a novel Schottky diode structure in an InGaP/GaAs HBT/BiFET process with a reduced turn-on voltage of 0.42 V and fully compatible with our current processes which requires no additional process steps.

DEVICE CONSIDERATIONS

High quality Schottky diodes use metal stacks that limit their diffusion into the semiconductor layer, such as Ti/Pt/Au. In addition to these metals well known in the III-V processes, other barrier layers have been used for some time in the Silicon world such as Ta, TaN, TaSiN, TiN, and WN. Among these, TaN has been shown to be the most effective [3], due to its high thermal stability, low resistivity, and low diffusion constants. Furthermore, in GaAs processes, TaN films were shown not to intermix with GaAs even after annealing at 550 °C, and to display very sharp interfaces [4].

Previous studies yielded TaN Schottky diodes with barriers lower than 0.5 V on n-type semiconductors. In a quest to increase the reverse breakdown voltage of Silicon high-voltage Schottky diodes, Kapoor et al. utilized TaN as an anode layer due to its physical strength and stability [5]. The TaN layer was deposited by a typical process of reactive sputtering of Ta in a plasma mixture of argon and nitrogen, to a 500 Å thickness. Both n- and p-type (100) silicon were used, with resistivity of 10 Ω-cm and 40 Ω-cm, respectively. The resulting diodes have measured barrier heights of 0.48 V for n-Si and between 0.54V and 0.67V for p-Si, depending on the particular annealing process. Similarly, Wu et al. [6] demonstrated TaN Schottky diodes on n-type Ge (100) with a resistivity of 0.043 Ω-cm. Diode samples with a TaN layer of 250 Å thickness showed a barrier height of 0.45 V, while diodes with the TaN thickness higher than 300 Å and up to 150 nm stabilized at 0.44 V.

The device we fabricated in this work is built in Skyworks' standard InGaP/GaAs HBT/BiFET processes with no added cost, such as additional masks, processing, or materials, since it uses the TaN process module regularly for our precision thin-film resistors. The new device uses TaN as the anode material and barrier between the first metal interconnect and the n-type GaAs, the cathode. Figure 1 shows a diagram of the structure. The device has the same definition as Skyworks' current Schottky diode except for the addition of the TaN layer, with an active area defined by the TaN plate size. The fabrication process involves the deposition of a TaN layer on top of the HBT collector layer after an opening is defined in the silicon nitride film. Other processing steps involve the collector etch, the collector contact formation at the sub-collector level and the layout of

the first metal interconnect, a Ti/Pt/Au metal stack, to contact both the TaN anode and collector contact terminals of the device. The device can be tested at the first metal layer.

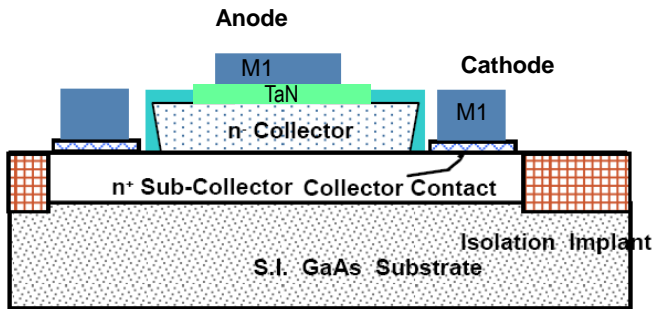


Figure 1. Schematic of the TaN Schottky diode.

A typical I-V characteristic curve is presented in Figure 2. The diode displays a forward bias, thermionic emission dominated region of more than seven decades in current at room temperature, with an average ideality factor of less than 1.07 and a turn-on voltage of about 0.42 V (Figure 3). The diodes also have an average reverse breakdown voltage of about 15 V as tested at a current density of 100 nA/μm².

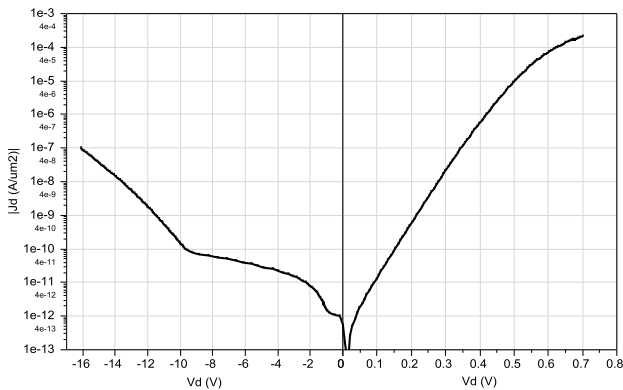


Figure 2. Forward and reverse I-V curves of a typical TaN Schottky diode (absolute values).

Measurements of the diode device parameters versus temperature yield a temperature coefficient of -1 mV/°C for the diode clamping voltage at a testing current density of 10 μA/μm². Additionally, small signal s-parameter measurements of the device over frequencies up to 10 GHz yield a flat capacitance density of 0.9 fF/μm² at 0 V. For a typical diode of 6 μm x 6 μm the diode series resistance is approximately 11 Ω while the capacitance is less than 33 fF. This results in a figure of merit $R_s C_0$ of only 0.36 picoseconds. Given the low turn-on voltage and the low figure of merit, these Schottky diodes can find practical application in high speed circuits such as detectors and mixers.

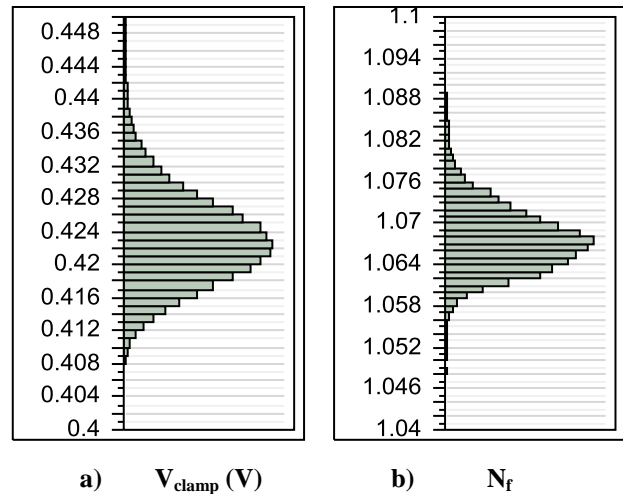


Figure 3. Distribution of measured diode turn-on voltage (a) and the extracted diode ideality factor (b) across a large sample.

MEASUREMENT OF DIODE BARRIER HEIGHT

Parametric measurement of the diodes was performed during in-line PCM (Process Control Module) test. Spot measurements were done by forcing the diode current between 10⁻¹⁰ A/μm² and 10⁻⁸ A/μm² and recoding the diode voltage. An exponential fit to the measurements yields the diode saturation current (I_s) and the diode ideality factor (N_f) based on the diode characteristic at these current densities:

$$I_d = I_s \exp \frac{V_d}{nKT} \quad (\text{Eq. 1})$$

These tests were performed at three different temperatures. The saturation current can be expressed as a function of the temperature as follows [7]:

$$I_s = AA^* T^2 \exp \frac{-\Phi_b}{kT} \quad (\text{Eq. 2})$$

where A is the area of the Schottky diode, A^* is the Richardson constant, T is the temperature in degrees Kelvin, Φ_b is the barrier height, and K is the Boltzmann's constant. Arranging the expression yields:

$$\ln \frac{I_s}{T^2} = \ln AA^* - \frac{\Phi_b}{kT} \quad (\text{Eq. 3})$$

Since the saturation current and the temperatures are known variables, by plotting $\ln(I_s/T^2)$ versus $1/T$ and fitting

with a straight line, we can determine the slope of the line as Φ_b/kT from which the barrier height is calculated.

Figure 4 shows the average extracted diode barrier height and its variation across the wafer as computed from a large sample. The mean barrier height is calculated at about 0.58 V, with a variation of about 30 mV.

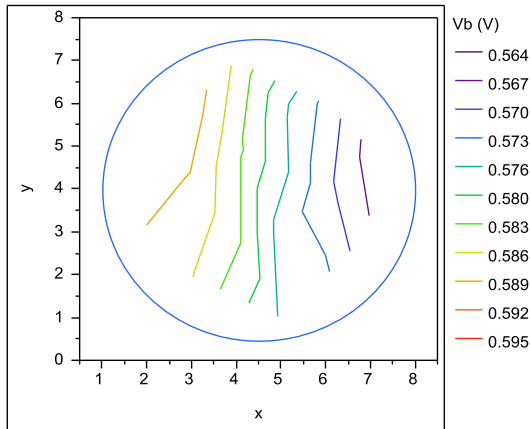


Figure 4. Averaged barrier height variation across wafer.

Similarly, from the line intercept, the Richardson constant A^* is extracted. The usual practice assumes that the Richardson constant for semiconductors such as GaAs is given by:

$$A^* = 120 \frac{m^*}{m_0} A/cm^2 K^2 \quad (\text{Eq. 4})$$

where (m^*/m_0) is the electron effective mass ratio, which is a property of the semiconductor and thus independent of the anode metallization. However, other studies have shown that the Richardson constant is influenced by other effects such as quantum-mechanical reflections at the interface and phonon scattering, but moreover by the quality of the Schottky junction and contact preparation [8]. The theoretical value is calculated at $8 A/cm^2 K^2$, while many experimental determinations of A^* show great variation between 1.5 and $290 \times A^* A/cm^2 K^2$, depending on the sample processing and preparation.

Figure 5 shows the Richardson constant statistics as extracted from our sample population. The results show that the values are only about twice the theoretical value. This result implies a very good quality of the junction with limited surface states. At the same time, Missous et al. [9] showed that the band structure of the anode metal can play a role in the deviation of the Richardson constant from the theoretical value. Unfortunately there are no reported experimental values for TaN Schottky diodes on GaAs semiconductor for reference.

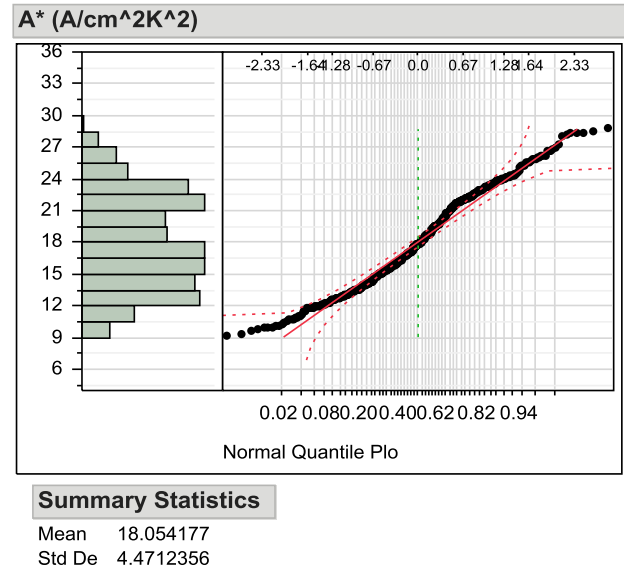


Figure 5. Distribution of the extracted Richardson constant A^* ($A/cm^2 K^2$).

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b

CONCLUSIONS

With this work we report on a novel Schottky diode with a lowered barrier height and turn-on voltage in InGaP/GaAs HBT/BiFET processes based on the use of TaN as the anode material. The new device shows low turn-on voltage of 0.42 V and good RF characteristics. This device adds flexibility to analog designs in III-V materials.

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ACRONYMS

HB T : Heterojunction Bipolar Transistor

TaN: Tantalum Nitride

BiFET: Bipolar / Field Effect Transistor

PCM: Process Control Module