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Characterization and modeling of temperature-dependent barrier heights and ideality factors in GaAs Schottky diodes

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Abstract

A semi-analytical model for Schottky diodes with ideality factors (η) greater than 1.00 is presented with an experimental verification from *n*-type GaAs Schottky diodes ($\eta = 1.00$–2.47 over $T = 83$–323 K). Adopting a correcting ideality factor in the distribution function, an accurate modeling of temperature-sensitive variations of current–voltage characteristics and accurate extraction of Schottky barriers are obtained with a modified Richardson constant. Temperature-dependent Schottky barriers ($\phi_{\rm bn} = 0.928\ {\rm V}|_{83\ {\rm K}}$–$0.837\ {\rm V}|_{323\ {\rm K}}$), obtained from the semi-analytical model, are consistent with the variation of the energy bandgap with temperature which is known to be the main cause for the change of Schottky barriers.

Keywords: Schottky barrier; Ideality factor; Richardson constant; Thermionic emission; GaAs; Temperature; Modeling; Characterization

1. Introduction

Schottky diode is a key component for implementing high performance high-electron mobility transistors (HEMTs) and metal–semiconductor field effect transistors (MESFETs) which are used for wide applications in digital, microwave, and optical detection systems [1,2]. In addition to the improvement of the barrier height and reliability, modeling and characterization of temperature-dependent variations in the current–voltage (*I*–*V*) characteristics and Schottky barriers in Schottky diodes has been a key issue for design and implementation of high performance integrated circuits with Schottky contacts. Among device models and characteristic parameters, it is essential to use appropriate models and accurate method for extracting Schottky barriers from experimental data. However, it is difficult to obtain Schottky diodes with an ideality factor $\eta = 1$ primarily due to non-ideal thermionic emissions, which include a thermionic-field emission, a quantum-mechanical tunneling, and generation-recombination in the space charge region.

Current–voltage characteristics of Schottky diodes, under forward bias, can be described by either a conventional model [3,4];

$$I = I_{\rm So} \exp\left(\frac{V}{\eta V_{\rm th}}\right) \tag{1}$$

with

$$I_{\rm So} \equiv SA^{**}T^2 \exp\left(-\frac{\phi_{\rm bno}}{V_{\rm th}}\right) \tag{2}$$

or empirical models [1,5–8];

$$I = I_{\rm Si} \exp\left(\frac{V}{\eta V_{\rm th}}\right) \tag{3}$$

with

$$I_{\rm Si} \equiv SA^{**}T^2 \exp\left(-\frac{\phi_{\rm bni}}{\eta V_{\rm th}}\right) \tag{4}$$

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where I_{So} and I_{Si} are reverse saturation current, S is the area, A^{**} is the Richardson constant, T is the temperature, V_{th} is the thermal voltage, η: ideality factor, $q\phi_{bn}$ and $q\phi_{bni}$ is the Schottky barrier heights. Both conventional and empirical models used the ideality factor as an experimental fitting parameter. Extracted Schottky barriers and I–V relations, therefore, are in lack of the accuracy in the description of practical Schottky diodes with $\eta \geqslant 1$ over a wide range of the temperature [9–11].

Based on the thermionic emission model [3] with a non-ideal emission/distribution factor in the carrier distribution function $f(E)$, we report a semi-analytical model effective for practical Schottky diodes with ideality factors $\eta \geqslant 1$ over a wide range of temperature. Considering the temperature-sensitive variations of ideality factors in the model, reliable Schottky barriers could be also obtained over a wide temperature range [3].

2. Semi-analytical schottky diode model

Under a forward bias in Schottky diodes, a current (I_F) established by the thermionic emission of carriers from the semiconductor into the Schottky metal can be obtained by [3]

$$I_F = \int_{\text{Thermionic Emision}} qSv_x \mathrm{d}n = \int_{E_F+q\phi_{bn}}^{\text{Cond Band}} qSv_x g_C(E) f(E) \mathrm{d}E \tag{5}$$

where q is the electronic charge, S is the area of the junction, v_x is the velocity of carriers in the direction of transport, and $E_F + q\phi_{bn}$ is the minimum energy required for the thermionic emission of electrons from the semiconductor into the Schottky metal, and $\mathrm{d}n = g_C(E)f(E)\mathrm{d}E$ which is differential carrier density available in the energy range between E and $E + \mathrm{d}E$. Considering only the thermionic emission in the carrier transport, the density of electronic state function $g_C(E)$ in the conduction band and the distribution function $f(E)$ can be described as, with m^* is the effective mass of electron, h is the Planck's constant and E_C is the minimum of conduction band,

$$g_C(E) = 4\pi(2m^*)^{3/2}\sqrt{E - E_C}/h^3 \tag{6}$$

and

$$f(E) = \exp\left[-\frac{(E - E_F)}{kT}\right]. \tag{7}$$

Including the tunneling and the field-assisted thermionic emission as well as the thermionic emission, especially at low-temperature, additional carriers contribute to the total current flow in Schottky diodes. Considering the temperature-dependent variation of ideality factor η, which is primarily caused by the deviation of the current flow from the thermionic emission process, total carriers with additional current flow mechanisms can be semi-analytically modeled by

$$\mathrm{d}n = \mathrm{d}n_o(1 + \Delta) = g_C(E)f(E)f_\delta(E)\mathrm{d}E \tag{8}$$

with a correcting factor $f_\delta(E) = \exp(\delta E/kT)$. With a correction factor Δ, extra carriers ($\Delta n = \mathrm{d}n_o \cdot \Delta$) contributing to the current due to additional emission mechanisms are adopted in the model. Additional carriers over the thermionic emission are modeled as a reduced energy barrier (δE) with effective energy barrier ($E - E_F - \delta E$) for thermionic emission. Reduced energy barrier δE empirically models an additional emission mechanism and therefore temperature-dependent. With this modification, we obtain a semi-analytical model, which is good for practical Schottky diodes over a wide range of the temperature, as

$$f(E)f_\delta(E) = \exp\left[-\frac{(E - E_F - \delta E)}{kT}\right] \equiv \exp\left[-\frac{(E - E_F)}{\eta kT}\right] \tag{9}$$

where η has been defined by

$$\eta = \frac{1}{1 - \frac{\delta E}{(E - E_F)}} \tag{10}$$

as a temperature-dependent ideality factor. In order to include non-ideal thermionic emissions, which include thermionic-field emission, quantum-mechanical tunneling, and recombination in the depletion region, an ideality factor η is introduced in the Maxwell–Boltzmann distribution function $f(E)$. With the ideality factor $\eta > 1$, more electrons will be injected due to the tunneling and the field-assisted thermionic emission in addition to the thermionic emission. Therefore, the electron density ($\mathrm{d}n$) in lightly doped semiconductors with a Maxwell–Boltzmann approximation, such as in typical Schottky diodes with a low doping concentration, can be described by

$$\mathrm{d}n = \frac{4\pi}{h^3}(2m^*)^{3/2}\sqrt{E - E_C}\exp\left[-\frac{(E - E_C + qV_n)}{\eta kT}\right]\mathrm{d}E \tag{11}$$

where $qV_n \equiv (E_C - E_F) = kT\ln(N_D/N_C)$ with a majority carrier density (N_D) and an effective density (N_C) of states in the conduction band.

Considering the kinetic energy ($E_k = E - E_C = m^*v^2/2$) for electrons in the conduction band, the forward current (I_F) in Schottky diodes can be re-described as

$$I_F = S\left(\frac{4\pi qm^*}{h^3}\right)(\eta kT)^2 \exp\left(-\frac{qV_n}{\eta kT}\right)\exp\left(-\frac{m^*v_{ox}^2}{2\eta kT}\right) \tag{12}$$

with $m^*v_{ox}^2/2 = q(V_{bi} - V)$, Schottky barrier height $\phi_{bn} = V_n + V_{bi}$, and a built-in voltage V_{bi}. We finally obtain a new semi-analytical current–voltage model for Schottky diodes with $\eta \geqslant 1$

$$I_F \equiv I_S \exp\left(\frac{qV}{\eta kT}\right) \tag{13}$$

where the reverse saturation current (I_S) and the temperature-dependent modified Richardson constant ($A^\#$) are defined, respectively, as