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Analysis of reverse current–voltage characteristics of Schottky diodes based on phonon-assisted tunneling including Frenkel emission mechanism

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Abstract

Reverse current–voltage characteristics of Al–GaP Schottky diodes are studied in the temperature range from 213 to 373 K. The results are explained on the basis of phonon-assisted electron tunneling from interface states to the semiconductor conduction band. At low bias and higher temperatures the Frenkel emission mechanism is taken into account. Electric field strength and the density of generating centres in the junction is estimated from the fit of experimental results with theory. The temperature and field dependence of the leakage current in thin film transistors extracted from Ref. [Solid-State Electron 38 (12) (1995) 2075] is also explained on the basis of our model. © 2002 Published by Elsevier Science Ltd.

Keywords: Schottky diodes; Phonon-assisted tunneling; Frenkel emission

1. Introduction

In most cases, the experimental current–voltage characteristics of real Schottky diodes deviate significantly from ideal ones calculated from commonly used the thermionic emission and diffusion theories. Many attempts have been made to describe the behavior of real Schottky diodes. An additional current mechanism, such as generation–recombination current [1,2], tunneling current [3–5] were taken into account in order to explain experimental observations.

Some models have been presented in which the influence of the presence of interface states on the current–voltage characteristics was included [6–10]. In these models the population of the interface states was assumed to have been changed by applied bias voltage.

The interface states being in equilibrium with the carrier concentration, the population at the interface states and also the barrier height are considered to be varied with reverse bias. Deviations from the ideal characteristics were attributed to the change of barrier height with applied voltage. But contrary to this interfacial model in Ref. [11] it was shown that the charge trapped in the interface states was independent of reverse bias voltage in the range of 0–4 V, the barrier height being strongly dependent on temperature and bias voltage for such diodes.

Recently new models based on Schottky barrier height inhomogeneity have been introduced to describe the non-ideal Schottky diodes [12–18]. The presence of inhomogeneities in the barrier height is shown to lead to an explanation of many anomalies in the experimental results, such as the temperature dependence of barrier height extracted from the current–voltage characteristics as well as curved behavior of the so-called Richardson plots. The ideality factor according to this model is a result of the deformation of the spatial barrier distribution when bias voltage is applied [13]. In a very recent paper [19] it has been shown that a better agreement of experimental data with theory in the frame of this model

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is obtained taking into account the tunneling type current flow through small local regions of junction with smaller barrier height values.

The main peculiarities of reverse current–voltage characteristics measured in a wide tempereture range for some Schottky diodes in [20–22] have been explained by involving the phonon-assisted electron tunneling from interface states to the semiconductor processes as a main carrier transport through the barrier mechanism. The temperature and voltage dependence of barrier height evaluated from the current–voltage measurements was explained by this mechanism as well [22]. In the case of Al–nInP diodes, the "soft" current–voltage characteristics were explained by the phonon-assisted tunneling mechanism taking into account Frenkel emission mechanism at higher temperatures.

This article presents the current dependence on reverse bias voltage measured at some selected temperatures of Al–GaP diode. The charge transport through the barrier is discussed in the light of the phonon-assisted tunneling theory including the Frenkel emission mechanism. We present also the analysis in the light of these mechanisms the results obtained by other authors.

2. Experimental results and comparison with theory

The surface barrier junctions were formed on the [1 1 1]-oriented GaP epitaxial structure. The density of free electrons extracted from capacitance–voltage measurements was 2.4×10^{17} cm^{-3} at room temperature. Under evaporation of 100 °C, an aluminium electrode with a diameter of 1.4 mm former the barrier, being surrounded by a ring of an ohmic contact. The barrier height of these diodes determined by C–V measurements was equal to (0.68 ± 0.02) eV. Reverse current I versus bias voltage V characteristics were measured in the temperature range of 213–373 K. The typical I–V curves of reverse-biased diodes at some selected temperatures are shown in Fig. 1 (open and close circles). One can see distinct peculiarities of the characteristics: dramatic temperature dependence at low bias and their crossing at a certain value of V in the high-voltage region.

The reverse current characteristics and its variation with temperature can be explained by a model developed in [22]. In accordance with this model, the charge transport through the barrier is governed by a process of phonon-assisted electron tunneling from interface states to the conduction band of the semiconductor. Assuming that all the released electrons are transferred through the barrier, the value of current I would equal to $AqNW_T$ where A is the area of metal–semiconductor junction, q is the electron charge, N is the electron density in the interface states and W_T is the electron tunneling rate from these states, which is a function of field strength F and temperature T. Thus, $I \sim W_T(F, T)$, which enables

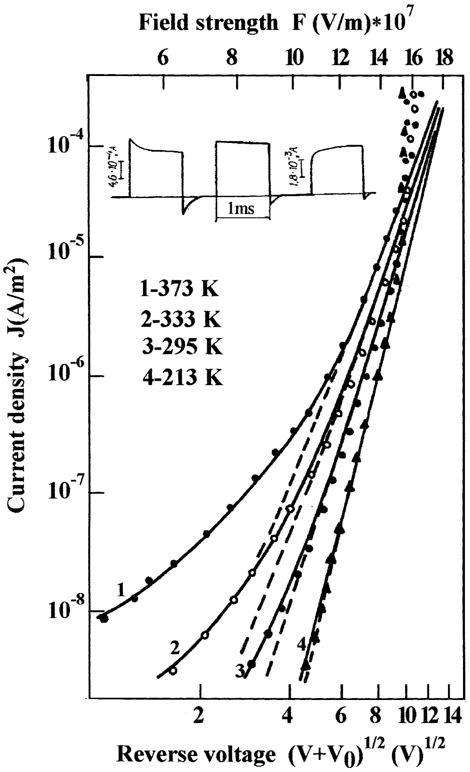


Fig. 1. The fit of logarithmic plot of the J vs. $(V + V_0)$ for the Al–GaP Schottky diode (dots) with theoretical J vs. F dependences computed by using phonon-assisted theory including Frenkel emission (solid lines) and by phonon-assisted theory only (dashed lines). Computation were performed for the parameters: $E_T = 0.70$ eV, $m^* = 0.34m_e$, $\hbar\omega = 44$ meV, $a = 6.0$, $N = 2 \times 10^{12}$ cm^{-2}, $\nu_0 = 5 \times 10^9$ s^{-1}, $\varepsilon = 10.75$ and the diffusion voltage $V_0 = 0.6$ V. The inset represents oscillograms of the current obtained under action of the voltage pulses.

us to compare the current dependences on bias voltage V obtained at different temperatures with the theoretical tunnel rate dependence on field strength. The transition rate $W_T(F, T)$ was computed using the multiphonon-tunneling theory (Eq. (16) in Ref. [24]). The calculation was performed for the electron effective mass $m^* = 0.34m_e$ [25] and for the phonon energy $\hbar\omega$ the energy of LO phonon in GaP of 44 meV [26] was taken. The value of the electron-phonon coupling constant a was chosen so as to get the best fit on the assumption that the field strength at the junction is proportional to $(V + V_0)^{1/2}$, V_0 being diffusion potential. The computed current density $J = qNW_T(F, T)$ dependences are represented in Fig. 1 by dashed lines. The comparison of the reverse J–V characteristics with theoretical J–F shows reasonable agreement. However, in the lower field strength region a slower increase of current with the rise of voltage is observed compared to the corresponding increase of the phonon-assisted carrier generation rate, and in this region experimental circles are over the theoretical curves. A considerable disagreement between theory and experiment is observed at higher temperatures. This disagreement is apparently caused by the fact that, in addition to the mechanism of tunnel emission there exists another mechanism for the electron emission which manifests itself at lower voltages and higher temperatures. Such a mechanism should be the Frenkel emission, which is characterized by a strong temperature dependence and a less pronounced dependence on the field strength than those of the tunneling mechanism. Total ionization rate of center involving the Frenkel emission will be $W = W_T + W_F$. W_F is calculated from the relation obtained by Frenkel [27]:

$$W_F = \nu_0 \exp\left[-\frac{E_T - q\sqrt{qF/\pi\varepsilon_0\varepsilon}}{kT}\right], \qquad (1)$$

where ν_0 is the frequency factor, E_T is the energy of thermal activation, F is the electric field strength, q is an electronic charge, ε_0 is the vacuum permittivity, and ε is the semiconductor dielectric constant equal to 10.75. Field strength dependences of the total emission rate W are shown in Fig. 1 by solid lines. It can be seen that calculated dependences fit well with experimental curves in the region of reverse bias $V < (8–9)$ V. At higher bias the reverse current increases more rapidly, than W rate and furthermore its temperature behavior undergoes such a transformation that curves obtained at different temperatures intersect. A rapid increase of reverse current in upper voltage region can be explained by involving an avalanche process, that is the electrons entering into the space charge region by tunneling may create carriers impact multiplication. This proposition is also supported by current kinetic measurements. The inset in Fig. 1 represents oscillograms of the current obtained under action of voltage pulses. At the low-voltage pulse a diminution of current from higher initial values to stationary ones is observed. At higher voltages the current increases, and in the duration of 0.3 ms it reaches stationary value. The increase in current value is regarded as carrier multiplication due to avalanche process.

Thus, in the low-field region and at higher temperatures the influence of the Frenkel emission into the carrier generation is quite significant. This fact has already been demonstrated in the case of diodes on p-InP [23] and once again we can demonstrate it for diodes on GaAs the I–V curves of which were presented in Ref. [22]. The fit of J–V dependences with the computed J–F dependences presented in Fig. 2 of Ref. [22] reveals divergence of experimental data from theory at low-bias voltages. This discrepancy can be eliminated including the Frenkel mechanism as it is shown in Fig. 2 of this paper.

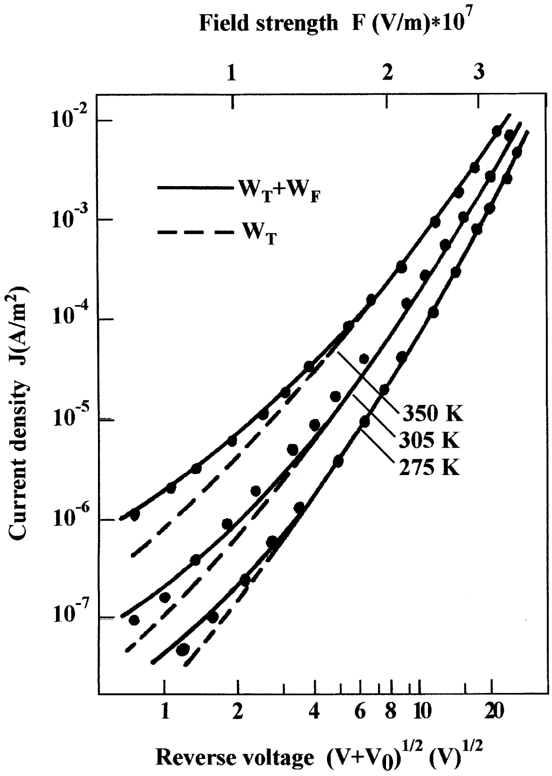
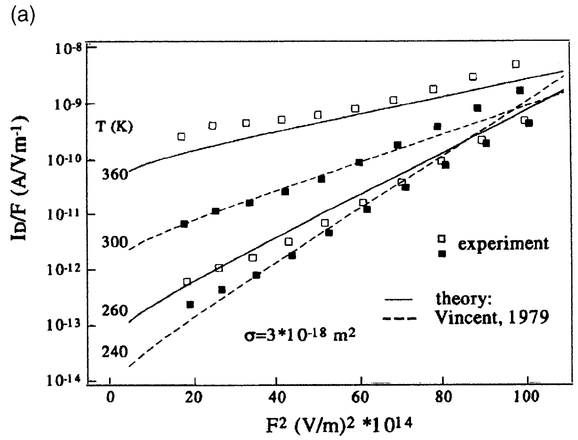


Fig. 2. The same dependences as in Fig. 1 for the Al–nGaAs diode fitted with theoretical J vs. F dependences computed using parameters: $E_T = 0.50$ eV, $m^* = 0.068m_e$, $\hbar\omega = 36$ meV, $a = 6.0$, $N = 6 \times 10^{12}$ cm^{-2}, $\nu_0 = 5 \times 10^9$ s^{-1}, $\varepsilon = 12.5$ and the diffusion voltage $V_0 = 0.28$ V.

It should be noted that phonon-assisted tunneling is recently involved to explain the temperature variations of I–V curves obtained in other devices, e.g. the authors of Ref. [28] have explained anomalous off-current (leakage current) in N-chanel polysilicon thin film transistors in terms of phonon-assisted tunneling. However, using Vincent's theory [29], the authors of [28] have not got a good fit theory and experiment, though in high-field region the tunneling mechanism must be dominant (Fig. 3a). In Fig. 3b these results are presented in a logarithmic plot of the I_D vs. F and fitted with theoretical curves of phonon-assisted tunneling rate dependence on field strength, calculated using multiphonon theory [24] (dashed lines). The field strength for this comparison was extracted from Fig. 8 in [28] and means the maximum field near the drain. The theoretical curves have been calculated by using $m^* = 0.33m_e$, LO phonon energy 52 meV. The fitting parameter a was found to be equal to 6. A good agreement between experiment and theory in this comparison is observed only in a region of high-field strength. Taking into account the Frenkel emission process one also obtains a better agreement between theory and experiment in a lower field strength region.



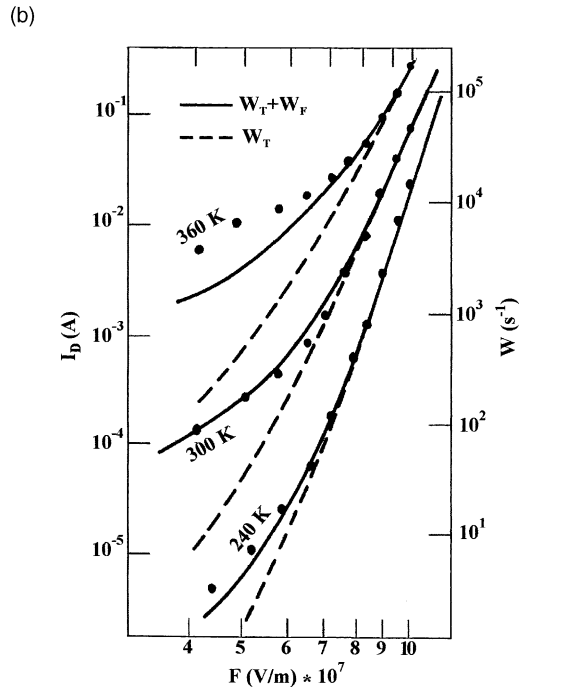


Fig. 3. (a) Dependences of I_D/F vs. F^2 represented from Ref. [28, Fig. 8] where the theoretical curves are also shown. (b) The fit of experimental results from the Fig. 3a with the total ionization rate $W_T + W_F$ and the tunneling rate W_T dependences on field strength computed using the parameters: $E_T = 0.59$ eV, $m^* = 0.34m_e$, $\hbar\omega = 52$ meV, $a = 6.0$, $\nu_0 = 2.4 \times 10^9$ s^{-1} and $\varepsilon = 12.0$.

3. Conclusions

We have presented an analysis of the reverse current in Schottky diodes based on I–V measurements at different temperatures. Our analysis shows that the main carriers generation mechanism in these devices is phonon-assisted electron tunneling from the states at the junction to the semiconductor conduction band. However, in the region of the low-bias voltages it is necessary additionally to consider the generation of carriers by the Frenkel mechanism that may dominate over tunneling at higher temperatures and low-electric fields. The density of generating centres is deduced from the conducted analysis. The temperature and bias dependence of the leakage current in polysilicon thin film transistors from Ref. [28] have also been explained on the basis of our model; it has become clear that these dependences in the region of high field are described better by Dalidchik 's expression than by Vincent's in [28]. In the region of low-field strength the Frenkel emission must also be taken into account.

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