POSSIBLE PHYSICAL ORIGINS OF NON-IDEAL TEMPERATURE DEPENDENCE OF CURRENT-VOLTAGE CHARACTERISTICS OF SCHOTTKY JUNCTIONS

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1. Introduction

Schottky junctions are a persistent object of semiconductor research. They are used in many semiconductor devices and structures, on one hand. On the other hand, their preparation and structure are very simple. (See, e.g. detector diodes used in the first decades of the last century.) So, they often are used as test structures in experiments, e.g., for studying new semiconductor materials.

Nevertheless, the physics behind their electrical characteristics is rather complicated, and there are different deviations from the ideal characteristics whose interpretation is disputed. One of these deviations is the non-ideal temperature dependence of current-voltage characteristics that is most widely interpreted by the Gaussian lateral inhomogeneity of the Schottky barrier height. However, this interpretation is incorrect in the opinion of some other authors. Nevertheless, this is practically the only explanation used in the literature for the interpretation of the anomalous experimental temperature dependence of current-voltage characteristics [1-6]. Probably most of the authors are not familiar with the other possible origins of this phenomenon.

2. Ideal and non-ideal characteristics

The ideal Schottky junctions have an abrupt, flat and laterally homogeneous interface between the metal and the semiconductor. It is assumed that the current via the junction is dominated by the thermionic emission of charge carriers above the potential barrier formed at the metal/semiconductor interface. This current mechanism can be expressed by Eq. (1):

$$J=J_0[\exp(\mathrm{q}V/n\mathrm{k}T)-1] \qquad (1a)$$

$$J_0=A^*T^2\exp(-\mathrm{q}\varphi_b/\mathrm{k}T) \qquad (1b)$$

where J is the current density via the junction, J_0 *is* the saturation current density, q the elementary charge, V the bias applied to the junction, n the ideality factor, k the Boltzmann constant, T the temperature, A^* the effective Richardson constant, and φ_b the Schottky barrier height

The main electrical characteristics of Schottky junctions are the current-voltage and the capacitance-voltage characteristics. Both characteristics depend on the Schottky barrier height and are influenced by energy states located in the semiconductor near the interface (so called interface states). The lateral inhomogeneity of the junction affects the both characteristics either. Current-voltage characteristics depend additionally on the actual current mechanism, while capacitance-voltage characteristics on the charge present near the interface.

It is expected on the basis of Eq. (1) that the current voltage characteristics exhibit strong temperature dependence: both the saturation current and the slope of the characteristics are temperature dependent, as it is presented in Fig. 1 for an $Al/Al_{0.75}Ga_{0.25}As/Al_{0.25}Ga_{0.75}As$ Schottky junction [7,8]. In ideal case, the ideality factor is independent of temperature, while the barrier height evaluated from the curves is influenced by the temperature dependence of the band gap. Indeed, in some cases the temperature dependence of Schottky barrier height evaluated for the thermionic emission theory from the current-voltage characteristics, is the same for n-type junctions, as that of the band gap (the barrier height slightly decreases with increasing temperature), while for p-type junctions the barrier height is independent of temperature [9-12].

But Schottky junctions often exhibit anomalous forward current-voltage characteristics with temperature dependent ideality factors [13-19]. This phenomenon, i.e., the increasing ideality factors with decreasing temperature (T_0 effect) were first reported by Padovani and Sumner [20]. The apparent barrier height obtained from the current-voltage characteristics for the thermionic emission is also strongly temperature dependent for these junctions. It decreases with decreasing temperature, but it is usually lower even at room temperature, than the barrier height obtained from the capacitance-voltage characteristics, as presented in Fig. 2 for four types of Schottky junctions prepared in different ways [21]. Therefore there is a current flow in these diodes at low temperatures with much higher magnitude than that following from the thermionic emission theory.

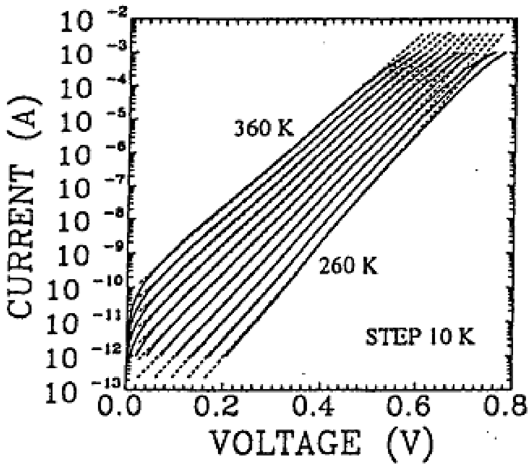

Fig. 1: Experimental current-voltage characteristics obtained in an $Al/Al_{0.75}Ga_{0.25}As/Al_{0.25}Ga_{0.75}As$ Schottky junction as a function of temperature (solid lines) and fitted theoretical curves (dashed lines) [7,8]

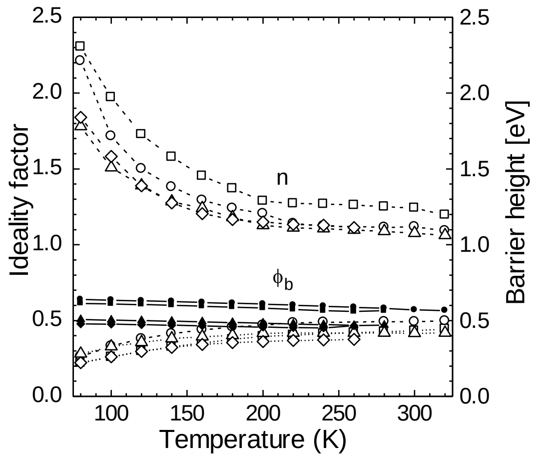

Fig. 2: The temperature dependence of ideality factor (n) and barrier height (φ_b) evaluated from the capacitance-voltage (solid symbols) and current-voltage (open symbols) characteristics for four different InP Schottky junctions [21]

3. Interpretations

Although this phenomenon is widely studied, the lateral inhomogeneity of the Schottky barrier height is practically the only explanation used in the literature for its interpretation, as mentioned in the Introduction. Concerning its possible mechanisms basically three different explanations was proposed, as the effect of interface states [22,23], the quantum-mechanical tunneling including the thermionic-field emission (TFE) [7,8,17,21,24-29], and the lateral distribution of barrier height [18,30-33].

However, other deviations of the actual Schottky junction from the ideal one can yield anomalous temperature dependence of the current-voltage characteristics, as e.g., inhomogeneous doping profile near the interface [34], the domination of space charge limited current over the thermionic emission [35], or even the bias dependence of the ideality factor [36].

As the effect of the lateral inhomogeneity is concerned, Werner and Güttler analyzed experimental current–voltage and capacitance-voltage characteristics by assuming a Gaussian lateral distribution of barrier height [18]. However, they obtained by their analysis that the mean barrier height decreases with increasing forward bias (see Ref. [18] p.1529). This is in contradiction with the existing models concerning the electrical behaviour of Schottky contacts, and also with the experiments. Nevertheless, most of the anomalous temperature dependence of current-voltage characteristics are explained by this model.

Sullivan and co-workers [32] studied the effect of lateral inhomogeneity of barrier height by numerical analysis assuming saddle-like passes with low barrier height. They obtained that such passes may yield the T_0 effect.

Horváth showed by numerical simulation that all features interpreted with the Gaussian lateral distribution of barrier height by Werner and Güttler, can be interpreted by the domination of the current with an anomalous high level of thermionic-field emission via the junction with the same accuracy [37]. He analyzed the possible origins of the anomalously high thermionic-field emission [29,37]. He also developed a method for the extraction of junction parameters (barrier height, effective Richardson constant, characteristic emission energy, and bias dependence of barrier height) from the current-voltage characteristics using the thermionic-field emission theory [7,8,29].

4. Summary

The interpretations of the anomalous temperature dependence of current-voltage characteristics of Schottky junctions (T_0 effect) are summarized and discussed briefly.

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