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LETTERS TO THE EDITOR

Comments on "Generalized Theory of Conduction in Schottky Barriers"

A paper with the above title has recently appeared in this Journal[1]. In it, the authors state that Bethe's theory of thermionic emission[2] assumes the absence of electron scattering in the depletion region, i.e. that the carrier mean-free-path l_n is greater than the depletion layer width. However, Bethe was well aware that scattering could take place without invalidating the thermionic emission theory, and gave as the criterion for its validity that l_n should be greater than the distance in which the barrier falls by an amount kT from its maximum value. Although his argument was largely intuitive, the criterion was subsequently derived more rigorously by Crowell and Sze[3].

There appears to be a misprint in Simmons and Taylor's eqn (17). The corrected equation can be written in the form $l_n \gg kT/qE_{\max}$, where $E_{\max}$ is the electric field at the top of the barrier, and is equivalent to the Bethe criterion. The development of Simmons and Taylor's argument runs closely parallel to that of Crowell and Sze, their eqn (15) for the generalized I–V characteristic being identical with Crowell and Sze's eqn (6).

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Comments on "Generalised Theory of Conduction in Schottky Barriers"

In the paper "Generalised theory of conduction in Schottky barriers" published in *Solid State Electronics*[1] Simmons and Taylor showed from eqn (21), (all equation numbers are the same as in[1]) that the electron concentration at the metal semiconductor boundary is given by eqn (22) instead of $n_\lambda = N_d e^{-\beta\phi_s*}$ assumed so far[2] when the diffusion theory is appropriate.

It is written in the paper that "for typical values of doping, thermal velocity and diffusion coefficient we have the condition $V_e \simeq V_{th}$" and therefore the current will be by a factor of two lower than the thermionic limit. In general this is not correct and one needs to look in[3] and[4], where the current given by (16) is investigated, for the correct relation of V_e and V_{th}.

The transit time of majority carriers through the space charge layer of Schottky diode is calculated by division of the quantity of all mobile charge carriers (electrons) in the space charge layer to the value of electron current from the semiconductor to the metal under the forward bias. This transit time is used as an estimation of the cutoff frequency of Schottky diodes. These times, given by (30) or (31), give an estimation of the time needed for electron transfer from the edge of the space charge layer with semiconductor bulk to the metal, in the stationary state under a constant forward bias. By substitution of x when $x < \lambda_D\sqrt{2}$ and $\lambda_D^2/2x$ when $x > \lambda_D/\sqrt{2}$ for the $D(x) = e^{-(x/\lambda_D)^2}\int_0^x e^{(x/\lambda_D)^2} dt$ it is easy to obtain for the mobile charge in the space charge layer under a forward bias

$$Q = |q|\left[N_a\lambda_D\frac{\sqrt{H}}{2}\operatorname{erf}\left(\frac{\lambda_n}{\lambda_D}\right) - \frac{I\lambda_D^2}{2D_n}\left(\frac{1}{2} + \ln 2 + \ln\left(\frac{\lambda_n}{\lambda_D}\right)\right)\right], \qquad (27)$$

where $\operatorname{erf}(x) = (2/\sqrt{\pi})\int_0^x e^{-\tau^2} d\tau$ is the tabulated error function. As $I = \alpha v_{th}(n_{\lambda_n} - N_d e^{-\beta\phi_s^*})$ it is clear from (27) that the second term is negligible in comparison with the first one. The first term of (27) changes very little with the change of the forward voltage because of the small changes of $\operatorname{erf}(\lambda_n/\lambda_D)$ in range of variation under the forward voltage change. Therefore there is not any need to take away all mobile charge in the space charge layer of the Schottky diode by electron current from the semiconductor to the metal during transient period after the voltage change. The redistribution of charge carriers in the space charge layer when the forward bias is removed takes place by a change of the drift current in the space charge layer. As the current from the semiconductor to the metal is a difference of the drift and diffusion currents in the space charge layer it is clear that the former current is much smaller than the later ones in Schottky diodes. From these considerations—negligible change of the mobile charge in the space charge layer when the applied voltage is changed and greater value of the drift current than the net electron current to the metal during the current adjustment to the changed applied voltage—it is clear that the corresponding transient times and cutoff frequencies of Schottky diodes could not be connected with the transit times given by (30) and (31). For usual doping levels, $10^{15} - 10^{17}$ cm^{-3}, Debye length is $10^{-5} - 10^{-6}$ cm and V_{th} is in $10^6 - 10^7$ cm/sec range. Usually the current theory of Schottky diodes is correct when the forward bias is smaller than $\phi_s^* - n/\beta$, $n \simeq 7$–10. If the forward bias increases further one needs to take into account ohmic voltage drop in the semiconductor bulk. But even up to this maximal value the transit times calculated by (30) is $10^{-10} - 10^{-8}$ sec for the above mentioned values of λ_D and V_{th}. On the other hand for example unbiased InP Schottky diode with $\phi_s^* \simeq 0.2$ V detects signals up to 500 GHz[5]. Point contact with Schottky barrier, W–Ge,