A method for Fermi energy measurements

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We describe a method of Fermi energy measurement, based on the analysis of thermionic emission and diffusion over a barrier with a built-in charge. The method can be applied to a variety of semiconductors and has been successfully tested by measuring the Fermi energy in GaAs. © *1998 American Institute of Physics.* [S0003-6951(98)01227-3]

In general, electronic current over a barrier depends on its height E_b, width w, the electronic mean free path l, the temperature T, and the Fermi energies E_{f_1}, E_{f_2} in semiconductor layers on both sides of the barrier (where $E_f \equiv E_F - E_C$ is defined relative to the conduction band edge in each semiconductor, see Fig. 1). As will be shown below [Eq. (4) for $w \to 0$] the $I-V$ characteristic for a ballistic barrier, i.e., for a barrier with $w < l$, has a remarkable feature that the derivative dI/dV exhibits a pronounced maximum when the bias voltage $eV \equiv E_{F_2} - E_{F_1}$ equals the Fermi level difference, $eV = E_{f_2} - E_{f_1}$. The latter condition is equivalent to $E_{C_1} = E_{C_2}$ (''flat bands''). Thus, for a ballistic barrier, one can easily extract from the $I-V$ characteristic the Fermi energy for one of the semiconductors, provided that the Fermi energy of the other semiconductor is known.

Unfortunately, in order that transport over the barrier was ballistic at room temperature, the barrier must be so narrow that tunneling and field emission components of the total current cannot be ignored. Because of this complication, it is impossible to determine E_f from the dI/dV curves in narrow barriers. On another hand, for wide barriers ($l < w$), where the tunneling and field emission contributions can be ignored, the $I-V$ curves do not exhibit a sharp maximum in dI/dV at $eV = E_{f_2} - E_{f_1}$ and therefore these curves cannot be employed for Fermi energy measurements. As a result, the temperature dependence of thermionic current, which is perhaps the simplest to measure transport characteristic, has only been used for measurements of the barrier height (if the Fermi energy is known) or for measurements of the Fermi energy (if the barrier height is known).

In this letter, a new method is proposed for the Fermi energy determination. It is based on thermionic emission and diffusion through a wide ($w > l$) but *charged* barrier. We shall demonstrate that the $I-V$ characteristics for such a barrier are similar to those for a ballistic barrier in that the derivative dI/dV has a pronounced maximum at $eV = E_{f_2} - E_{f_1}$. In the charged wide barrier, this effect occurs due to the built-in field, which converts the diffusive regime of transport into thermionic emission. This enables direct measurements of the Fermi energy in structures with wide barriers without the knowledge of other system parameters.

In the following we shall assume that the barrier height is much larger than kT and that the electron motion in the barrier layer is diffusive.

The current density in the barrier is given by the drift-diffusion equation:[1]

$$J = eD \frac{\partial n}{\partial x} + en\mu \mathscr{E}^*, \tag{1}$$

where $\mathscr{E}^*$ is the electric field in the barrier, $\mathscr{E}^* \equiv (V^*/w)$ and V^* is the potential drop, $eV^* \equiv E_B(w) - E_B(0) = eV - (E_{f_2} - E_{f_1}) - \chi_1(V) - \chi_2(V)$. Here $E_B(x)$ is the conduction band edge in the barrier, $\chi_1(V)$ and $\chi_2(V)$ are the band bendings near the barrier, which can be calculated from the Poisson equation [see Fig. 1(a)], and D and μ are, respectively, the diffusion coefficient and the mobility of electrons in the barrier, which are connected by the Einstein relation

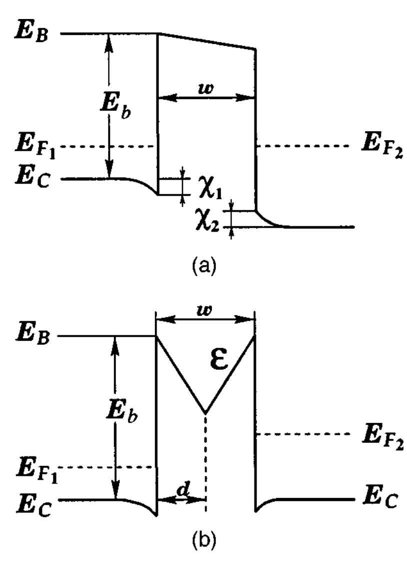

FIG. 1. (a) Potential offsets near the barrier. (b) V-shaped potential barrier with electric field $\mathscr{E}$.

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$eD=\mu kT$. Having assumed $E_B \gg kT$, we neglect the variation of $\mathcal{E}^*$ owing to the injected charge in the barrier.

Solving Eq. (1) with respect to n, we find

$$n(x)=Ce^{-(e\mathcal{E}^* x/kT)}+\frac{J}{e\mu\mathcal{E}^*}. \tag{2}$$

The boundary conditions on the concentration at both interfaces are described in terms of the current flow as follows:

$$J=-ev_R[\alpha n_1-n(0)], \quad J=ev_R[\alpha n_2-n(w)], \tag{3}$$

where $\alpha \equiv N_C^{(b)}/N_C=(m_b^*/m^*)^{3/2}$. Here n_1 and n_2 are the concentrations of carriers in the semiconductor layers 1 and 2 at energies above the barrier energy ($n_i = N_C e^{-(E_b-\chi_i(V)-E_{f_i})/kT}$), $n(0)$ and $n(w)$ are the electron densities in the barrier near the interfaces; N_C and $N_C^{(b)}$ are the densities of states and m^* and m_b^* the effective masses of electrons in the semiconductor layers and in the barrier respectively. $v_R=\sqrt{kT/2\pi m_b^*}$ is the Richardson velocity, corresponding to the effective mass of electrons in the barrier.[2]

Using Eq. (2) with the boundary conditions (3) and the continuity equation for the current one obtains an expression for the current in the heterojunction as a function of the bias voltage:

$$J=\frac{N_c e^{-E_b-\chi_2(V)-E_{f_2}/kT}(1-e^{-eV/kT})}{\frac{1}{ev_R}(1+e^{-eV^*/kT})+\frac{\alpha w}{e\mu V^*}(1-e^{-eV^*/kT})}. \tag{4}$$

The derivative dI/dV of Eq. (4) has a pronounced maximum at $eV=E_{f_2}-E_{f_1}$ *only* for ballistic barriers ($w \to 0$).

In order to examine the thermionic diffusion through a charged barrier, we consider the simple case of a positively charged plane in the middle of the AlGaAs barrier which results in a V-shaped potential of the barrier with electrical field $\mathcal{E}$, see Fig. 1(b).

In full analogy with the previous case, for the barrier of width $w=2d$ and height E_b at temperature T, the solution of thermionic diffusion equations gives the following expression for the current density as a function of applied voltage V:

$$J=\frac{\frac{e\mu\mathcal{E}_1\mathcal{E}_2}{\mathcal{E}_2-\mathcal{E}_1}(B_2e^{-e\mathcal{E}_2 d/kT}-B_1e^{-e\mathcal{E}_1 d/kT})}{1-\frac{e\mu\mathcal{E}_1\mathcal{E}_2}{\mathcal{E}_2-\mathcal{E}_1}(A_2e^{-e\mathcal{E}_2 d/kT}-A_1e^{-e\mathcal{E}_1 d/kT})}, \tag{5}$$

where $\mathcal{E}_1=-\mathcal{E}+V^*/w$; $\mathcal{E}_2=\mathcal{E}+V^*/w$;

$$A_1=\frac{1}{\alpha e v_R}\left(1-\frac{v_R\alpha}{\mu\mathcal{E}_1}\right); \quad A_2=-\frac{1}{\alpha e v_R}\left(1+\frac{v_R\alpha}{\mu\mathcal{E}_2}\right)e^{e\mathcal{E}_2 w/kT}, \tag{6}$$

$$B_1=\frac{N_c}{\alpha}e^{-(E_b-E_{f_1}+\chi_1)/kT}; \quad B_2=\frac{N_c}{\alpha}e^{-(E_b-E_{f_2}-\chi_2)/kT}e^{e\mathcal{E}_2 w/kT}. \tag{7}$$

Here, $\mathcal{E}$ is positive for positively charged barrier. For a neutral barrier ($\mathcal{E}=0$) expression (5) reduces to (4). Thus, when $\mathcal{E}=0$ and $\mu \ll (ev_R\alpha w/kT)$ (the mean free path is shorter than the width of the barrier) the current is significantly suppressed relatively to its ballistic value, and dI/dV is not peaked at $eV=E_{f_2}-E_{f_1}$, as shown in Fig. 2(a).

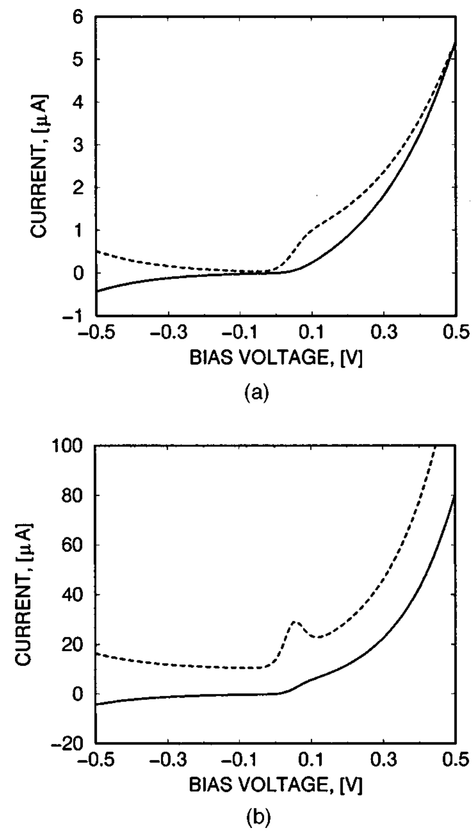

FIG. 2. (a) Theoretical $I-V$ curve (solid line) and its derivative (dashed line) for uncharged barrier with $\mu=500\ \mathrm{cm^2/V\,s}$, $E_b=300$ meV, $E_{f_1}=40$ meV, $E_{f_2}=90$ meV at $T=153$ K. (b) Theoretical $I-V$ curve (solid line) and its derivative (dashed line) for charged barrier with $\mu=500\ \mathrm{cm^2/V\,s}$, $E_b=300$ meV, $\mathcal{E}=2\times10^4$ V/cm, $E_{f_1}=40$ meV, $E_{f_2}=90$ meV at $T=167$ K.

For a diffusive and charged ($\mathcal{E}\neq 0$) barrier the thermionic current behaves similar to the ballistic case when $|\mathcal{E}| \gg (\alpha v_R/\mu)$ and the dI/dV has a pronounced maximum at $eV=E_{f_2}-E_{f_1}$. Fig. 2(b) shows that the peak at the dI/dV is still well resolved even when $|\mathcal{E}|=(\alpha v_R/\mu)$. The condition $|\mathcal{E}|>\alpha v_R/\mu$ is equivalent to $l\mathcal{E}>kT/e$, as discussed in detail by Grinberg and Luryi.[3]

In order to check these equations and their utility for Fermi energy measurement, we have grown by molecular-beam epitaxy (MBE) two samples containing GaAs/$Al_{0.3}Ga_{0.7}As$ heterojunction as shown in the insets of Figs. 3(a) and 3(b). As seen from the figures, the samples are almost identical ($N_D=3\times10^{18}\ \mathrm{cm^{-3}}$ in the top GaAs layer and $N_D=1\times10^{18}\ \mathrm{cm^{-3}}$ in the bottom one) with the only difference being in the barriers. In sample (b) δ-doping of Si with sheet carrier concentration $\sigma=1\times10^{12}\ \mathrm{cm^{-2}}$ was introduced in the middle of the barrier. The highest possible field in the barrier that can be produced by Si donors is given by $\mathcal{E}=(E_B-E_D)/d$, where E_D is the donor energy level. For Si in $Al_{0.3}Ga_{0.7}As$ we obtain $\mathcal{E}\approx 2\times10^4$ V/cm, which corresponds according to Gauss' law $\mathcal{E}=e\sigma/2\epsilon$ to $\sigma\approx 2.7\times10^{11}\ \mathrm{cm^{-2}}$. It means that roughly 1/4 of Si donors are ionized.

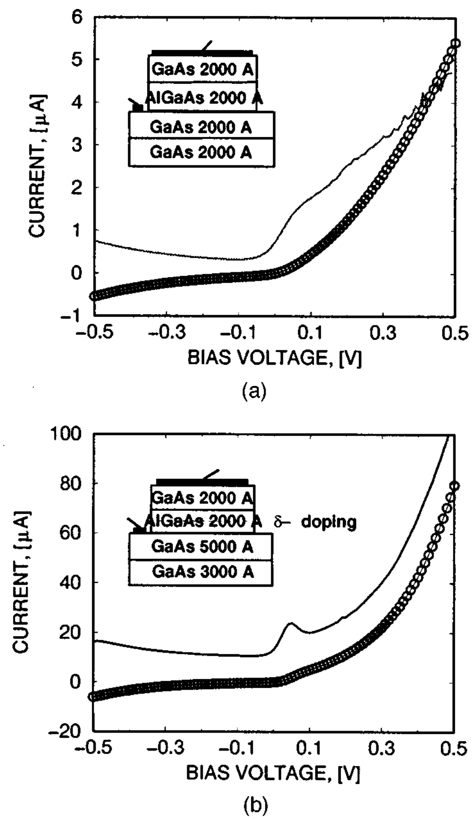

FIG. 3. (a) Experimental curve (circles) and its derivative for uncharged barrier. The inset–vertical junction for $I-V$ measurements and sample structure with undoped barrier. (b) Experimental curve (circles) and its derivative for charged barrier. The inset–vertical junction for $I-V$ measurements and sample structure with doped barrier.

Standard photolithographic technique was used to fabricate two-terminal small area vertical junctions [see the insets of Figs. 3(a) and 3(b)]. Separate shallow ohmic contacts were provided to the top and bottom GaAs layers. The junctions were utilized for $I-V$ characteristics measurements.

$I-V$ characteristics of the junctions were measured at $T\approx 160$ K in a two-terminal configuration, using HP 4145B Semiconductor Parameter Analyzer. This temperature was chosen in order to diminish the contribution of the ohmic contacts resistance to the junction resistance, which were comparable at room temperature.

The $I-V$ curve of the junction with uncharged barrier is shown in Fig. 3(a). The shape of the curve is similar to the shape of the theoretical curve [Fig. 2(a)], which is plotted for the parameters of our structure. The derivative dI/dV does not exhibit any local maximum.

At the same time, as expected, the dI/dV curve for the case of the charged barrier shows a well-pronounced peak at $V\approx 50$ meV [see Fig. 3(b)]. Moreover, the shape of the $I-V$ curve is similar to the one depicted in Fig. 2(b). Although the variation in all structure parameters used in the theoretical curve would drastically change the shape of the $I-V$ characteristic the peak in dI/dV and its position will stay in place as long as $|\mathscr{E}|\geqslant(\alpha v_R/\mu)$ and $E_{f_2}-E_{f_1}$ is fixed. In our structures with charged barriers the condition $|\mathscr{E}|\geqslant(\alpha v_R/\mu)$ is satisfied for $\mu\geqslant 500\ \mathrm{cm^2/V\,s}$. Note, that in order to observe ''real'' ballistic transport in our structures the requirement for the mobility in the barrier would be $\mu\gg 3500\ \mathrm{cm^2/V\,s}$, which is hard to meet. We do not know the exact value of the mobility in our AlGaAs barriers. However, $\mu\geqslant 500\ \mathrm{cm^2/V\,s}$ is a reasonable value at $T\approx 155$ K for the AlGaAs grown by MBE. We would like to emphasize again that the exact value of μ is of no importance as long as it exceeds $500\ \mathrm{cm^2/V\,s}$.

The position of the peak in dI/dV in Fig. 3(b), namely $eV\approx 50$ meV is consistent with the value $E_{f_2}-E_{f_1}=54$ meV where $E_{f_1}=38$ meV for $n_1=1\times 10^{18}\ \mathrm{cm^{-3}}$ and $E_{f_2}=92$ meV for $n_2=3\times 10^{18}\ \mathrm{cm^{-3}}$. It proves that the thermionic emission through a charged wide barrier can be utilized as a new experimental tool for measurements of the Fermi energy in a variety of semiconductors. This method is extremely simple and quite reliable.

We have demonstrated that introduction of fixed charge into a heterostructure barrier significantly changes the $I-V$ characteristics of thermionic diffusion, in such a way that the derivative curve exhibits a well-defined peak when the Fermi levels on both sides of the junction are aligned by the applied voltage. This situation can be successfully realized in experiment and used for determination of Fermi energy in semiconductors. Previously, only ballistic barriers were thought to possess a similar property, which was therefore difficult to employ in practice.

In a separate publication[4] we report the application of the present technique to measuring the Fermi level in InGaAs layers with ultraheavy tin doping. The concentration dependence of E_f, which was previously inaccessible to direct measurements, exhibits strikingly anomalous features.

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[1] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley-Interscience, New York, 1981).
[2] A. A. Grinberg and S. Luryi, IEEE Trans. Electron Devices (to be published).
[3] A. A. Grinberg and S. Luryi, Solid-State Electron. **35**, 1299 (1992).
[4] A. Tsukernik, A. Palevski, S. Luryi, and A. Cho (unpublished).