Barrier Enhancement Mechanisms in Heterodimensional Contacts and Their Effect on Current Transport

Amro Anwar, *Student Member, IEEE*, and Bahram Nabet

***Abstract*—It has been shown that, in a three-dimensional (3-D) to two-dimensional (2-D) contact system, the quantized nature of the energy of the 2-D system imposes important changes on thermionic emission of carriers from a 3-D metal to two-dimensional electron gas (2DEG). Interestingly, in actual devices, barrier heights higher than what is theorized based on the first confined state are measured. In this paper, we introduce an additional mechanism that explains barrier height enhancement in 3-D–2-D contacts, which is due to the repulsive Coloumbic force that is exerted by the 2DEG on the thermionically emitted electrons. An analytical derivation of the barrier height due to this effect is given and total thermionic emission current is derived. These results are particularly important for design and understanding of device behavior for low-noise photodetectors in front end optical receivers. The electron cloud model presented for the reservoir of mobile charges that are free to move in response to charged particle or electromagnetic waves implies that any means of interaction that disturbs the equilibrium of the electron cloud have strong signature at the contact, as well as the temporal response of the induced disturbance. This can be effective for low-power-detection applications.**

***Index Terms*—Barrier height, Coulomb force, Schottky contact, 2DEG, thermionic emission.**

I. Introduction

There is a growing technological challenge and demand for high-speed and compact integrated electronics necessitating high-mobility low-power consumption semiconductors with potential of ultra-large-scale integration of electronic and opto-electronic circuitry. One avenue to fulfill these requirements is to utilize reduced dimensional semiconductors where carriers are spatially confined to less than three dimensions. Spatial confinement causes the carriers' energy states to be quantized rather then continuous, as is the case of unbounded carriers in bulk semiconductor devices. With recent progress in semiconductor growth and processing technologies, low-dimensional systems have become practically realizable; hence, the study of contact properties to these systems has become increasingly important [1], [2].

One of the interesting physical problems encountered in employing these systems is the inevitable interface between two-dimensional (2-D) semiconductor and three-dimensional (3-D) system of the external circuit.

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A. Anwar is with Cisco Systems, San Jose, CA 95134 USA.

B. Nabet is with the Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA 19104 USA.

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A relevant example is the case where carriers have to be collected or injected to the 2-D system via metal contacts. Thus, it is crucial to study the impact of such interaction between the heterodimensional systems so as to predict when this contact might be beneficial for specific applications.

Schottky metal contact to two-dimensional electron gas (2DEG) is an example of interfacing between heterodimensional systems, i.e., contact between 3-D metal and 2DEG semiconductor. Schottky metal contact to 2DEG has been shown to be very promising in different microwave and millimeter-wave applications [3], [4]. In the context of investigating the transport across the Schottky 3-D metal to 2DEG semiconductor, it is relevant to mention that the reduced dimensional nature of the confined 2DEG substantially effects its transport properties [5], [6]. In photodetection applications, these result in reducing the dark current of heterodimensional contact photodetectors [2]. The reduction in dark current improves the sensitivity of the photodetectors, as well as increases the operating bandwidth, enhancing the overall detection performance of optical receivers.

In the following section, we review a theoretical model we proposed [7] describing the current across the Schottky contact between two heterodimensional systems, specifically, a metal and 2-D semiconductor. This is followed by examining the effect of the 2DEG carriers in modulation-doped structures on the barrier height, which lead to modification of transport across the barrier. We derive analytical expressions for change of barrier height due to the effect of the electron cloud, thus modifying thermionic current description. We close by presenting general discussions and conclusions.

II. Thermionic Emission Between 2DEG and 3-D

With a semiclassical approach we have previously shown [7] a thermionic emission model for charge transfer from metal, considered a 3-D system to 2DEG. The current density $J_{\rm sm}$ between a 2-D semiconductor and 3-D metal can be described by the number of carriers with velocity in the direction perpendicular to the junction and with energies above $E_f + q\phi_B$ as

$$J_{\rm sm} = \int_{n(E_f+q\phi_{Bn})}^{n(\infty)} q\vartheta_x dn \tag{1}$$

where E_f is the Fermi level energy, and ϕ_{Bn} is the Schottky barrier height, as depicted in Fig. 1. Noting that $dn = N(E)f(E)dE$, where $N(E)$ is the 2-D density of state

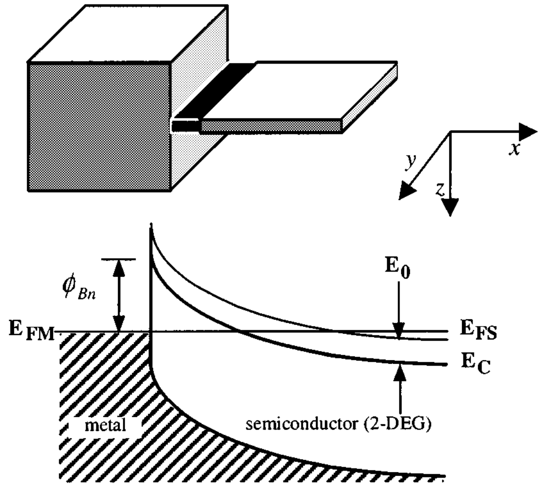

Fig. 1. (top) Metal contact to 2DEG. (bottom) Energy band diagram.

function and $f(E)$ is the electron density distribution function, the current density from semiconductor to metal can be derived as previously demonstrated [7]. Considering that under thermal equilibrium the flux of carriers from metal to semiconductor is the reverse of flux in the opposite direction, total thermionic emission current becomes

$$J_{\text{th}} = A_{2D}^{*} T^{3/2} \exp\left[-\frac{q\phi_{Bn}}{k_B T}\right] \exp\left[-\frac{E_o}{k_B T}\right] \times \left(\exp\left[-\frac{qV}{k_B T}\right] - 1\right) \text{ A/cm} \quad (2)$$

where

$$A_{2D}^{*} = \frac{2q}{h^2}\sqrt{2\pi m^* k_B^3} \text{ A/cm} \cdot \text{K}^{2/3} \quad (3)$$

is a new 2-D to 3-D thermionic emission coefficient expressing a 2-D Richardson constant. From (3), a total reverse bias quasi-saturation current can be extracted as

$$I_{2D} = W A_{2D}^{*} T^{3/2} \exp\left(-\frac{q\phi_{Bn}}{k_B T}\right) \exp\left(-\frac{E_o}{k_B T}\right) \text{ A} \quad (4)$$

where W is the length of the contact. In comparison, the conventional (3-D) thermionic emission current is

$$I_{3-D} = A_{\text{eff}} A^* T^2 \exp\left(-\frac{q\phi_{Bn}}{k_B T}\right) \exp\left(\frac{q\Delta\phi_{\text{im}}}{k_B T}\right) \text{ A} \quad (5)$$

where A_{eff} is the effective contact area. It is seen that clear distinctions exist between the current transfer from metal to 2-D and 3-D systems. Firstly, it is observed that, in the 2-D system, the barrier height has been increased by the value of the first confined state, as indicated by the term $\exp(-E_o/k_B T)$. Secondly, the prefactor of the exponential term in (5) depends on the 2-D density of states function, which is smaller than that of the bulk; in (5) we also included the conventional image force barrier lowering potential $q\Delta\phi_{\text{im}}$. In addition to physical device dimensions, the prefactor is based on terms due to the integration of carriers with velocity components confined to a plane, rather than a volume, as is the case for a 3-D system. Finally, it is noted that the temperature dependence of current is different in the two cases.

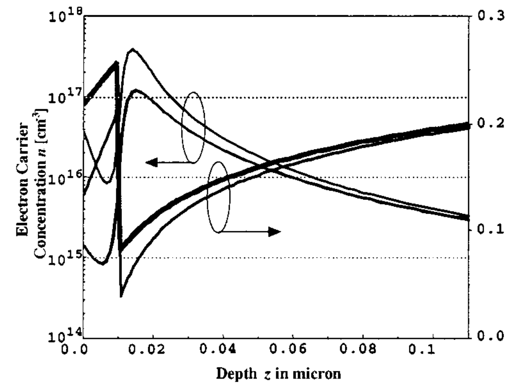

Fig. 2. Carrier density and conduction band bending along the depth z in the GaAs side of the AlGaAs/GaAs heterostructure for two AlGaAs dopings 3×10^{17} and 6×10^{17} cm^{-3}.

III. Electron Cloud Effect on Barrier Height

Examining the thermionic emission current above shows that, while the classical threshold for emission is determined by the minimum of the conduction band, the quantum threshold is raised above that by the zero point energy of the first ground state E_o. On the other hand, experimentally measured barrier heights [9] have shown enhanced values that cannot be solely explained by this energy quantization effect. In the following, a unique mechanism accounting for the barrier enhancement is introduced and formalized.

This mechanism for barrier enhancement is pertinent to structures where reduced dimensionality is achieved by carrier confinement between bandgap discontinuity at the higher bandgap semiconductor end, and the conduction band bending on the other end. Fig. 2 shows the conduction band and carrier concentration distribution of an example heterostructure of AlGaAs/GaAs for two doping concentrations. The carrier distribution, as shown in Fig. 2, presents locally uncompensated carriers charging the small bandgap semiconductor. If a Schottky contact is made to the GaAs side, a depletion region will separate the metal surface from this electron cloud. We suggest that this charge, electron cloud, adds an additional mechanism of barrier height enhancement in 3-D-2DEG contacts, due to the repulsive Coloumbic force that it exerts on the thermionically emitted electrons. This Coloumbic repulsive force will be proportional to the uncompensated carrier concentration in the 2DEG, as well as being a function of the device physical parameters, and the applied bias.

Since the carrier concentration varies in the direction of growth, the vertical z-direction (as shown in Fig. 2), will lead to a depletion region $d_{\text{dep}}(z)$, which is also z-dependent, as schematically shown in Fig. 3. Thus, estimation of the effect of the electron cloud on the barrier potential requires a 2-D treatment of the Poisson equation. In the present development, we calculate the aggregate effect of the electron cloud's line charges at distance $R(z, \ell)$ from a metal arbitrary point z'.

We consider the electron cloud carrier concentration as arranged line charges varying in the x–z-plane. The notion of line charge implies that the carriers extend indefinitely in the perpendicular plane. This is a valid assumption since actual devices under investigation are of planar structures.

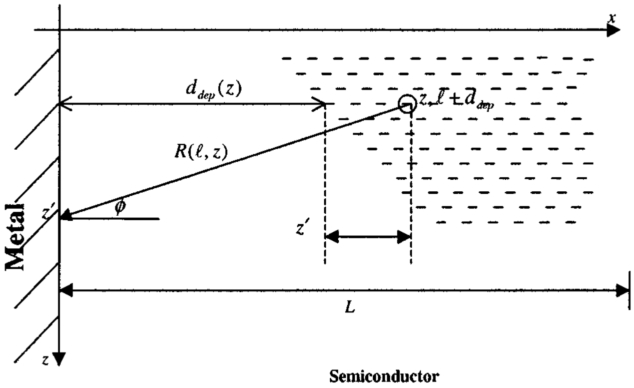

Fig. 3. 2-D description of the contact between metal and semiconductor.

In fact, modeling based on line charges is more appropriate than point charge model or infinite plane of carriers. For simplicity, the carrier concentration $n(z)$ along the lateral x-direction is assumed to be zero in the depletion region $d_{\mathrm{dep}}(z)$ and constant beyond that point in the electron cloud region.

The electric field due to one line charge at an arbitrary point z' of the metal interface in the cylindrical coordinate is well known to be

$$E_r = -\frac{qn(z)}{2\pi r \varepsilon_s R(\ell, z)}\hat{e}_r \tag{6}$$

where ε_s is the static dielectric constant of the semiconductor. Under these conditions, the potential seen by electrons emitted laterally in the x-direction at point z' at the metal interface is given by

$$V_{e-e}(z') = -\int E \cdot dx = -\int E_r \cos\phi dr \tag{7}$$

$$V_{e-e}(z') = -\frac{qn(z)\cdot(\ell + d)}{2\pi\varepsilon_s R(\ell, z)} \tag{8}$$

where $R(\ell, z) = \sqrt{(z - z')^2 + (\ell + d)^2}$.

This is the potential seen at z' due to one line charge, to account for the whole channel, we sum the effect of the line charges in x and z to arrive at

$$V_{e-e.c.}(z') = -\int_{z=z_o}^{z_m}\int_{\ell=d}^{L}\frac{qn(z)\cdot(\ell + d)}{2\pi\varepsilon_s R(\ell, z)}d\ell dz. \tag{9}$$

This expression is easily integrated with respect to ℓ and can be evaluated numerically in the z-direction.

The evaluation of the integral (9) gives the electron cloud barrier enhancement term $\Delta\phi_{e-e.c.} = -V_{e-e.c.}$ at the arbitrary point z'. For the AlGaAs/GaAs heterostructure, we evaluate (9) for three dopings of the AlGaAs. Fig. 4 shows the variation of barrier enhancement $\Delta\phi_{e-e.c.}$ along the metal interface for these dopings. It is seen that higher doping concentrations *increase* the barrier height.

The evaluation of the reverse-bias quasi-saturation thermionic emission current is then straightforward and is achieved by integration of the current density over the contact area as

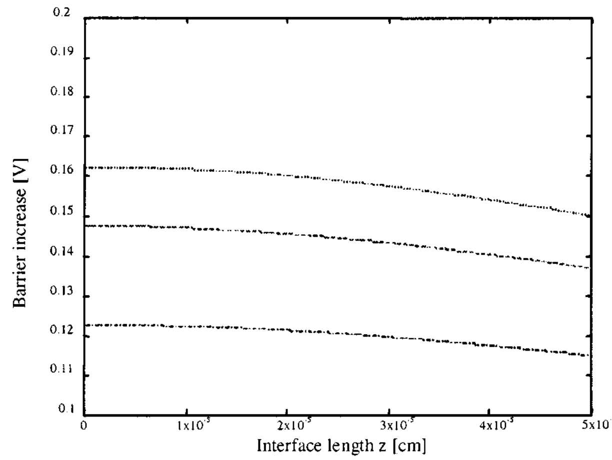

Fig. 4. Electron cloud potential at the metal interface for various N_d dopings 2×10^{17}, 6×10^{17}, and 8×10^{17} cm^{-3}.

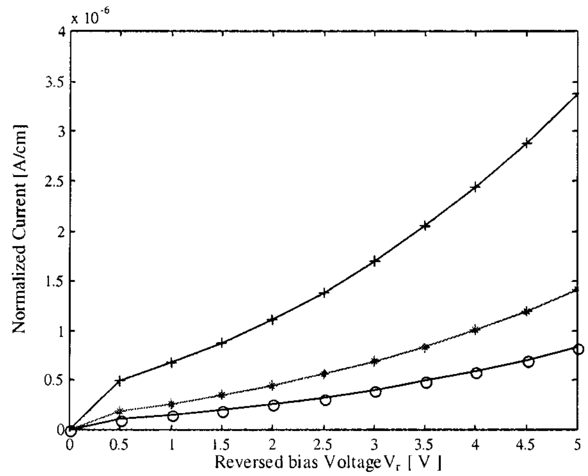

Fig. 5. Normalized reverse bias quasi-saturation variation with applied bias for dopings of 2×10^{17}, 6×10^{17}, and 8×10^{17} cm^{-3}.

$$I(V_r) = WA^*T^2\int \exp\left(\frac{-\phi_{Bn} + \Delta\phi_{\mathrm{im}} - \Delta\phi_{e-e.c.}}{k_BT}\right)dz. \tag{10}$$

The current–voltage relationship for the three dopings of AlGaAs is shown in Fig. 5. This figure emphasizes that, if the carrier concentration in the channel increases, the barrier height will also *increase* and, hence, current will *reduce* according to (10). This is opposite to what is observed in high electron-mobility transistor (HEMT) devices where conduction is proportional to the amount of confined charges. Experimental reports of Schottky contact to modulation-doped 2DEG are in agreement with this unconventional behavior [9], [10]. The upper limit to the expected decrease of current with increase of doping is when tunneling becomes the main means of current transport.

A similar technique for modulating the Schottky barrier height [11] is achieved by growing a thin p^+ layer; the n-type semiconductor before deposition of the metal contact. This layer tailors the doping profile in the depletion region, thus enhancing the barrier height. That mechanism has shown [2] a measured enhancement in the Schottky barrier height and lowering of the dark current in Schottky photodiodes. It has also been shown [12] that incorporation of a thin (few atomic layers) doped layer at the interface of a heterojunction can alter the bandgap discontinuity due to the dipole created at the heterointerface. The major difference between the process described in this paper and the referenced studies in terms of application, however, is that, here, the amount of electron concentration and, hence, the barrier, can be modulated by gating the structure or by changing the thickness of the n-AlGaAs layer or its doping. This means that, despite the pinning of the Fermi level, the barrier height can be controlled within a range of tens of megaelectronvolts in a modulation-doped structure.

IV. Discussion and Conclusions

The derivation of thermionic emission current between a 3-D-metal and 2DEG reflects the impact of reduced dimensionality nature of the 2DEG. This is shown in a modified Richardson constant and temperature characteristics. These properties stem from the emission of carriers from a system whose density of states is energy independent, as is the case for 2-D. Furthermore, one may picture emission from discrete energy cross-sectional areas corresponding to the 2-D side subbands into continuous states in the metal side instead of the emission from a continuous energy cross-sectional area. The confinement of the 2DEG in one direction causes the quantization of their energy states and enhances the barrier height by the amount of the first confined state, further reducing the thermionic emission current. Another important mechanism of barrier height enhancement was theorized based on the effect of the confined and uncompensated charges in the narrow gap material on the emitted electrons. The repulsive force due to this electron cloud was shown to be responsible for further increase of the barrier height. These behaviors should be observable at room temperature and are in agreement with experimental data.

The picture presented here addresses the separation of the carriers form their source, and can lead to a host of devices that utilize the fact that the low bandgap semiconductor in the heterostructure is not locally neutral, but unlike space charge regions, consists of mobile carriers. In these modulation-doped heterostructures, the electron cloud in the reservoir between the conduction band discontinuity and the Schottky barrier consists of mobile charges, which are free to move in response to a charged particle or electromagnetic waves. As such, any means of interaction that disturbs the equilibrium of the electron cloud could have a strong signature at the contact, as well as the temporal response of the induced disturbance. This can be effective for low-power detection applications.

References

[1] H. Okada, K. Jinushi, N. Wu, T. Hashizume, and H. Hasegawa, "Novel wire transistor structure with in-plane gate using direct Schottky contacts to 2DEG," *Jpn. J. Appl. Phys.*, vol. 34, pp. 1315–1319, 1995.

[2] B. Nabet, "A heterojunction metal–semiconductor–metal photodetector," *IEEE Photon. Tech. Lett.*, vol. 9, pp. 223–225, Feb. 1997.

[3] W. C. B. Peatman, T. W. Crowe, and M. Shur, "A novel Schottky/2-DEG diode for millimeter- and submillimeter-wave multiplier applications," *IEEE Electron. Device Lett.*, vol. 13, pp. 11–13, Jan. 1992.

[4] P. J. Koh, W. C. B. Peatman, and T. W. Crowe, "Millimeter wave tripler evaluation of a metal/2-DEG Schottky diode varactor," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 73–75, Mar. 1995.

[5] S. G. Petrosyan and A. Y. Shik, "Contact phenomena in a two-dimensional electron gas," *Sov. Phys. Semconduct.*, vol. 23, no. 6, pp. 2229–2239, June 1989.

[6] B. L. Gelmont, W. Peatman, and M. Shur, "Heterodimensional Schottky metal-two-dimensional electron gas interfaces," *J. Vac. Sci. Technol. B, Microelectron.*, vol. 11, no. 14, pp. 1670–1674, Aug. 1993.

[7] F. Castro, A. Anwar, and B. Nabet, "Schottky contact between metal and two-dimensional electron gas: Device applications to low-noise optical detectors," in *Proc. SBMO/IEEE MTT-S Int. Microwave Optoelectron. Conf.*, Natal, Brazil, Aug. 11–14, 1997, pp. 323–326.

[8] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley, 1981.

[9] T. Ytterdal, M. S. Shur, M. Hurt, and W. C. Peatman, "Enhancement of Schottky barrier height in heterodimensional metal–semiconductor contacts," *Appl. Phys. Lett.*, vol. 70, no. 4, pp. 441–442, Jan. 1997.

[10] A. Anwar, B. Nabet, J. Culp, and F. Castro, "Effect of electron confinement on thermionic emission current in a modulation doped heterostructure," *J. Appl. Phys.*, vol. 85, no. 5, pp. 2663–2666, Mar. 1999.

[11] M. C. Ho, Y. He, T. P. Chin, B. w. Liang, and C. W. Tu, "Enhancement of effective Schottky barrier height on n-type InP," *Electron. Lett.*, vol. 28, no. 1, pp. 68–70, Jan. 1992.

[12] F. Capasso, A. Y. Cho, K. Mohammed, and P. W. Foy, *Appl. Phys. Lett.*, vol. 46, pp. 664–666, 1985.

Amro Anwar (S'99), photograph and biography not available at time of publication.

Bahram Nabet, photograph and biography not available at time of publication.