Current flow past an etched barrier: field emission from a two-dimensional electron gas

D. H. Cobden$^1$, G. Pilling$^1$, R. Parthasarathy$^1$, P. L. McEuen$^1$, I. M. Castleton$^2$, E. H. Linfield$^2$, D. A. Ritchie$^2$, and G. A. C. Jones$^2$

$^1$ Department of Physics, University of California and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
$^2$ Cavendish Laboratory, Madingley Road, Cambridge, CB3 OHE, UK

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Abstract. – We find that, under appropriate conditions, electrons can pass a barrier etched across a two-dimensional electron gas (2DEG) by field emission from the GaAs/AlGaAs heterojunction into a second, low-density 2DEG formed deep in the substrate. The current-voltage characteristics exhibit a rapid increase in the current at the field emission threshold and intrinsic bistability above this threshold, consistent with a heating instability occurring in the second 2DEG. These results may explain similar behaviour recently seen in a number of front-gated devices by several groups.

Extensive studies of two-dimensional electron systems over the last two decades have relied on the ability to trap electrons at an interface between two materials with different band energies. Most popular amongst these systems is the high-mobility GaAs/Al$_x$Ga$_{1-x}$As heterojunction [1]. Here the electrons are confined principally by attraction to remote donors placed in the AlGaAs. However, in order for there to be complete confinement there must also exist an electric field in the GaAs substrate pushing the electrons towards the heterojunction. In practice, this substrate field is typically provided by negative charge on residual acceptors in the substrate and surface boundary conditions [2]. A very interesting situation arises if this confinement field vanishes. The electrons are then predicted to be very weakly bound at the interface, by the work function of the 2DEG, as discussed by Groshev and Schoen [3]. The work function depends sensitively on the density of the 2DEG and is strongly influenced by many-body effects such as the image potential. Because of the weak confinement, field emission of electrons into the substrate may be anticipated in a weak electric field applied perpendicular to the interface.

In this letter we discuss a simple device that demonstrates the field emission of electrons from a 2DEG. We find that a current can flow past an etched barrier in a 2DEG if the...
substrate field is adjusted using a positive voltage applied to a back gate. The electrons
are field emitted from the 2DEG and travel underneath the etched barrier. The magnetic
field dependence demonstrates that the current is carried via a low-density 2DEG formed
at an upside-down heterojunction below the uppermost GaAs substrate layer. The observed
current-voltage characteristics in this regime are highly nonlinear. Above a threshold bias
the current rises rapidly and exhibits bistability. We show that this bistability results from
thermal runaway due to heating of the (initially localized) electrons in lower 2DEG by the
field-emitted electrons from the upper 2DEG.

These results are important for three reasons. First, they demonstrate a simple geometry
in which the process of field emission from a 2DEG can be studied. Second, they illustrate
the existence of a thermal instability in an initially insulating, low-density 2DEG. Finally,
they offer insight into a number of recent experiments on transport across a lateral barrier
[4, 5, 6, 7] on a GaAs/AlGaAs heterostructure. The latter experiments all revealed very similar
behaviour to that reported here. Various explanations were put forward, including the heating
of an accidental puddle of electrons within the barrier [5], impurities exchanging electrons [6],
and interplay with gate leakage current [8]. In many of these cases, however, the bistability
occurred under conditions when the substrate field vanished (after illumination), indicating
that the mechanism proposed here may explain these experiments as well.

The device geometry, heterostructure composition and measurement configuration are in-
dicated in fig. 1(a). The back gate is a 50 nm layer of n+ GaAs which is contacted separately
from the 2DEG using in situ ion-beam patterning (see ref. [9]). Above this is a 500 nm AlGaAs
barrier, followed by 500 nm of GaAs at the top of which is the normal heterojunction. At
$V_g = 0$, a 2DEG of density $2.5 \times 10^{11}$ cm$^{-2}$ and mobility $3.0 \times 10^5$ cm$^2$V$^{-1}$s$^{-1}$ resides at this
heterojunction. The barriers in the 2DEG are produced by electron-beam lithography and wet
etching on the arms of a Hall-bar mesa. The etch width ($\sim 200$ nm) and depth ($\sim 50$ nm)
create a potential barrier at the heterojunction that is known to be hundreds of millivolts high
[10]; enough to make the barriers completely insulating at both room and low temperature
[11].

Fig. 1(b) shows the $I$-$V$ characteristics of a barrier at temperature $T = 4.2$ K for different
gate voltages $V_g$. A bias $V$ of up to 100 mV is applied to one contact, and the current $I$
is measured with a virtual-earth current preamplifier attached to the other contact. As $V_g$
is increased from zero, $I$ is zero until $V_g = 1.53$ V. Then, up to $V_g \gg 1.60$ V, $I$ remains zero at low
$V$ but grows rapidly above a threshold bias. Near this threshold there is bistability between a
low- and a high-current state, causing hysteresis between up and down sweep directions
(indicated by arrows at $V_g = 1.54$ V) [12]. The threshold bias (the value of $V$ at which $I$
in the high-current state extrapolates to zero) decreases towards a limiting value $V_{lim} \approx 40$
mV as $V_g$ is increased. At $V_g \gg 1.60$ V the bistability disappears and simultaneously the
conductance at $V = 0$ becomes finite. Measurements on a number of barriers revealed very
similar characteristics.

To understand these results, we first consider the effect of $V_g$ on the unetched 2DEG.
The solid line in fig. 2(a) is the density, $n_1$, of the 2DEG deduced from the low-field Hall
efficiency of an unetched region, while the filled circles here are the values of $n_1$ obtained
from Shubnikov-de Haas oscillations. We see that $n_1$ increases linearly with $V_g$ up to about
1.4 V, above which it levels off at $3.5 \times 10^{11}$ cm$^{-2}$. The reason for this levelling off [1]
is the population of a second 2DEG, as is illustrated by the band diagrams in fig. 3. At $V_g = 0$
the lower heterojunction, at the bottom of the 500 nm GaAs layer, is far above $E_F$ and the
electrons are tightly confined by the electric field in the GaAs to the upper heterojunction.
The linear increase in $n_1$ for $V_g < 1.4$ V is determined by the capacitance between the upper
heterojunction and the back gate, whose separation is 1020 nm. At $V_g = 1.4$ V the lower
heterojunction reaches the Fermi level $E_F$ and a second 2DEG forms there. For $V_g > 1.4$ V, the band in the GaAs remains almost flat, and $n_1$ remains constant. The density $n_2$ in the lower 2DEG then increases according to the dashed line.

Now we examine the properties of the barrier over the same range of $V_g$. Fig. 2(b) shows the differential conductance, $\frac{dI}{dV}$, at $V = 0$ and 100 mV. Both become finite only for $V_g \geq 1.5$ V. The inset shows the variation with magnetic field $B$ of $\frac{dI}{dV} = (\frac{dI}{dV})^{-1}$, at $V = 100$ mV and $V_g = 1.72$ V. It is roughly linear for $B \geq 0.5$ T, suggestive of a Hall resistance. The same is true at other values of $V_g$. If at each $V_g$ we interpret the slope as a Hall coefficient, $R_H = \frac{d(\frac{dI}{dV})}{dB}$, and convert it to a number density $(eR_H)^{-1}$, we obtain the open circles plotted in fig. 2 (a). The results closely follow the predicted behaviour of $n_2$.

Armed with our understanding of the behaviour of the upper and lower 2DEGs, we can readily interpret these results. The explanation is sketched in fig. 4(a). The repulsive potential created by the etched surface is smallest at the lower heterojunction, as indicated by the contours. It is therefore clear why the barrier only conducts once the gate voltage is such that the lower heterojunction is populated. The current flows past the barrier along the lower 2DEG. The onset of nonlinear conduction in the I-V curves can also be understood. To get from the upper to the lower 2DEG, the electrons must be field emitted from the upper 2DEG.

By analogy with field emission in metals, this happens above a characteristic electric field and hence a well defined source-drain bias.

To understand this in more detail, we need to consider the transfer rate from the upper to the lower 2DEG and the conductance $G_2$ of the lower 2DEG. We first discuss the variation of $G_2$ with $V_g$. For $V_g < 1.4$ V, $n_2 = 0$ and hence $G_2 = 0$. For a range of $V_g$ above this, $n_2$ is low enough that localization by disorder causes $G_2$ to be activated, i.e., $G_2 \approx G_0 \exp[-E_a/k_BT]$. As $n_2$ increases, the high-$T$ conductance $G_0$ should increase while the activation energy $E_a$ decreases until at some point $G_2$ becomes measurable at 4.2 K. It is reasonable that this happens at $V_g = 1.6$ V, when $n_2 \sim 3 \times 10^{10}$ cm$^{-2}$. In support of this we find from additional measurements that the linear-response barrier conductance is activated, with $E_a = 1.3$ mV and $G_0 = 38$ mS at $V_g = 1.66$ V, and that $E_a$ decreases while $G_0$ increases with increasing $V_g$. This scenario is confirmed by the observation that the magnetoresistance of the I-V curves accurately reflects the expected Hall effect of the lower 2DEG, whose two-terminal magnetoresistance is dominated by its Hall resistance at high $B$. In other words, the on-state resistance is dominated by the resistance of the lower 2DEG.

Having understood the role of the lower 2DEG, we can now ask how field emission from the upper 2DEG is related to the nonlinearity and bistability seen in fig. 1(b). As $V$ is increased, the electric field between the upper and lower heterojunctions grows. When the field perpendicular to the 2DEG reaches some value we expect the rate of electron escape from the upper 2DEG on the negative (left) side of the barrier to rise rapidly, by analogy with field emission from a metal cathode. This is indicated in fig. 4(b). Variational calculations of the 2D subband wavefunctions imply that a 2DEG eventually becomes unstable (to field emission) as the substrate potential is lowered \[3\]. We can check that within our self-consistent simulation the onset of field emission is sudden. We take the situation in fig. 3 with the lower 2DEG occupied, and incorporate a potential drop $\Delta V$ across the GaAs well \[4\]. At $\Delta V = 0$, all the lower-energy wavefunctions are strongly localized to one or the other side of the well. However, as $\Delta V$ is increased, at some point the second subband on the left side of the well develops a tail on the right side. The integrated probability in the tail can be approximated by $\exp[(\Delta V - V_{fe})/\delta]$, where $V_{fe}$ and $d$ are constants. Since once this tail forms electrons in the second subband can spill out of the upper 2DEG across the well, we identify $V_{fe}$ with the field emission threshold within the model. Correspondingly, $\delta$ is the characteristic bias range over which field emission starts. The value of $V_{fe}$ obtained depends on the acceptor concentration...
in the GaAs layer. A concentration of $2.0 \times 10^{11}$ cm$^{-3}$ gives $V_{fe} = 31$ mV and $\delta = 1.6$ mV. For all acceptor concentrations we find $\delta \ll V_0$, implying that the onset of field emission is indeed sudden.

If field emission only increased the transfer rate across the well, then the current would quickly be limited by $G_2$ and the $I$-$V$ curves would simply show a turn-on above a threshold voltage. However, each field-emitted electron delivers an excess energy of up to $e\Delta V$ to the lower 2DEG, where $\Delta V$ is the potential difference between the upper and lower 2DEGs in the field emission region. This may be expected to cause the electron temperature $T^*$ to increase, thereby decreasing $G_2$ and increasing the current. Within such a scenario a bistability arises naturally [15]. We illustrate this by representing the barrier by the simplified equivalent circuit in the inset to fig. 4(c), consisting of a diode of turn-on voltage $V_{fe}$ in series with the activated conductance $G_0 \exp[-E_a/k_BT^*]$. $T^*$ increases monotonically with $VI$, the power dissipated. Our justification for neglecting the resistance for current returning from the lower to the upper 2DEG is that the hot electrons can easily traverse the well once they have passed the barrier. Such a circuit exhibits an S-shaped bistable region in its $I$-$V$ characteristic, due to thermal runaway in the lower 2DEG [3]. Fig. 4(c) shows a characteristic generated using a simple proportional relationship, $T^* = \alpha IV$ and reasonable values of the parameters (see figure caption) chosen for similarity to the data at $V_g = 1.55$ V in fig. 1(b).

According to this model, the limiting threshold bias, $V_{lim}$, defined in the discussion of fig. 1(b), is a measure of the field-emission threshold, $V_{fe}$. One may therefore estimate the electric field for field emission to be $E_{fe} \sim V_{lim}/d$, where $d$ is the GaAs well width. For this device we get $(40$ mV$)/(0.5$ mm$) = 8 \times 10^4$ Vm$^{-1}$. This is much lower than for 3D metals, where field emission typically occurs at around $10^9$ Vm$^{-1}$ [16]. Of particular interest is the situation where there is no doping in the substrate, and the intrinsic work function [3] may be investigated. Our simulations indicate that $E_{fe}$ is around $5 \times 10^3$ Vm$^{-1}$ in this limit. Note that the threshold bias should depend on the geometry of the emitter, with a sharper point resulting in a lower threshold. Future work will address these issues.

Finally, we note that escape from a 2DEG can easily occur whenever the potential is nearly flat in the GaAs substrate. In the present devices, this situation is brought about by making $V_g$ sufficiently positive. It is known, however, that illumination with an LED at low temperatures also flattens the bands in the GaAs by neutralizing acceptors deep in the substrate [3]. Indeed, we have previously seen very similar behaviour in etched barriers on standard heterostructures with no back gate, but only after illumination with red light at 4.2 K [4], and we have subsequently found that a voltage applied to the chip carrier has much the same effect on the characteristics as has $V_g$ in the present devices. These standard heterostructures too have an upside-down heterojunction around 1$\mu$m below the normal one, at the top of the superlattice buffer. In Refs. [3, 4] infrared illumination was also applied before the nonlinear and bistable behaviour was observed. We therefore believe that the mechanism described here can explain the puzzling behaviour seen in their standard heterostructure devices as well.

In conclusion, we have demonstrated a nonlinear device that relies on the field emission of electrons from a 2DEG trapped at a heterointerface to a second 2DEG beneath it. The device exhibits bistable $I$-$V$’s associated with a thermal runaway in the second 2DEG due to heating by the field-emitted electrons. This study opens the way for investigations of the work function of 2D metals [3]. Our experiments show that electrons can escape from 2DEGs more easily than is often appreciated, and this may help to explain the frequent occurrence of nonlinear/bistable behaviour in a variety of heterostructure devices.

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Fig. 1 - (a) Schematic view of a device, indicating the layer structure and measurement configuration. (b) $I-V$ characteristics at a series of $V_g$. In each case $V$ was swept up and down once.

Fig. 2 - (a) Area electron densities vs $V_g$. The density of the upper 2DEG, $n_1$, is obtained both from Hall (solid trace) and Shubnikov-de Haas (filled circles) measurements. The dashed line is the predicted density $n_2$ of the lower 2DEG. (b) Differential conductance vs $V_g$ at $V = 1$ mV and 100 mV. The inset shows an example of the linear variation of $\frac{dV}{dI}$ with magnetic field at $V = 100$ mV, from which the density values plotted as open circles in (a) are derived.

Fig. 3. - Self-consistent band profiles in the unetched heterostructure at three values of $V_g$, separated by 0.5 V offsets for clarity. The electron density, shaded in black, is superimposed. Uniform negative acceptor densities of $2.0 \times 10^{14}$ cm$^{-3}$ in the GaAs and $6.5 \times 10^{15}$ cm$^{-3}$ in the AlGaAs were included, the latter being chosen to bring the lower heterojunction to $E_F$ at $V_g = 1.4$ V.

Fig. 4. - Depiction of current flow past an etched barrier. Contours of potential energy are sketched in, the highest being the one closest to the etched surface. (a) At low bias, only equilibrium transfer occurs between upper and lower 2DEGs. (b) At higher bias (negative on the left), electrons can be field emitted from the upper 2DEG near the barrier. (c) Characteristic of the simplified equivalent circuit (inset) taking $V_{fe} = 38$ mV, $G_0 = 2$ mS, $E_a = 2.5$ meV, and $T^* = \alpha IV$ with $\alpha = 2$ K/pW.

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Transitions between the two current states are governed by transition rates which are functions of $V$, resulting in a random telegraph signal if $V$ is held at a value in the bistable region.

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(a) Schematic of the device with an etched trench. The layers include:
- 10 nm GaAs
- 40 nm n-AlGaAs
- 20 nm AlGaAs
- 500 nm GaAs
- 500 nm AlGaAs
- 50 nm n+ GaAs

(b) I-V characteristics with contours labeled in $V_e(V)$.
$V_g (V) = 1.72$ V

$dV/dI (k\Omega) = 20$

$B (T) = 1$

$V_g = 100 \text{ mV}$

$V = 0$

$V = 100 \text{ mV}$

$\text{Density} (10^{11} \text{ cm}^{-2})$

$\text{upper 2DEG, } n_1$

$\text{lower 2DEG, } n_2$

$V = 0$

$dI/dV (\mu S)$
The figure shows the self-consistent potential as a function of depth for a device with a 2D electron gas (2DEG) in GaAs and AlGaAs layers. The Fermi level, $E_F$, is indicated at various depths. The back gate voltage, $V_g$, is shown to increase from 0.0 V at the surface to +2.5 V at the back gate. The temperature is $T = 4.2$ K.
