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Initial Study of Ballistic Effects for the Operation of GaAs FET Devices

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Ballistic electron motion at high velocity in the [100] direction in GaAs at both 77°K and room temperature has been determined by current-voltage data on thin layers. Molecular beam epitaxial abrupt layers .4-.5 microns thick with N^+ ohmic contacts on both sides, have been tested, and ballistic motion occurs below .5V applied voltage. Layers with a donor density of 1 x 10^{15}/cm^3, and layers with an acceptor density of 1 x 10^{15}/c both yield space charge limited current data to agree with the correspondin

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ballistic transport models developed.

Average electron velocity values five times higher than that obtainable in a standard FET are now possible for both 77°K and room temperature in such ballistic electron motion. Although the standard FET geometry, even with short gates, is precluded by thick depletion layers into lightly doped layers, from both the exposed surface and the interface with the semi-insulating substrate, it has been concluded that a ballistic electron transistor with a geometry similar to that of the permeable base transistor is possible for very high speed, high frequency, low noise performance.

Summary

Experimental and theoretical work has been done to determine the fastest possible electron motion in GaAs. The experimental results are that current-voltage curves show that the electrons move in a nearly ballistic manner, to remarkably high velocities, up to .5 micron distances, even at room temperature. The motion appears to be predominantly in the direction of the electric force, chosen to be in the [100] direction for the highest velocity. The velocity increases to about 1 x 10^8 cm/s at just over .5V applied voltage, which also corresponds to electron energy of about .5V. This is well above the .3V where scattering to the [111] upper valleys in the conduction band was expected, but .5V does correspond to the upper valleys in the [100] direction.

The devices were grown by molecular beam epitaxy, .4-.5 microns thick, and were doped at either 1 x $10^{15}/cm^3$ net donors or 1 x $10^{15}/cm^3$ net acceptors. Extra care was needed to make very low contact resistance. The devices were measured for I(V) characteristics both C.W. to .3-.4V and pulsed to 2.5V, at room temperature and at 77°K. Very little difference occurred with temperature, since only one fifth of the collisions at room temperature are due to ambient phonons; the other collisions are the launching of new phonons.

Theoretical predictions of the expected I(V) curves for ballistic motion, and for space charge effects brought on by the thinness of the layers, were made for both small positive (net donors) and small negative (net acceptors) ambient fixed charge density. The experimental data were then checked against the theoretical curves with good agreement for thin layers and voltage below .5V.

The main reason for overlooking the possibility of such substantial ballistic motion in the past appears to be that the short mean free paths were measured and published from avalanche experiments, and the effects of collisions were also over-estimated. Theoretically, two or three collisions occur during the time of flight of the low energy (<.5V) electrons across a .5 μm layer. The energy loss is modest, since each phonon is only .037 eV, and the most probable angle of flight after collisions is 5-10° off the original direction. Thus the device current, heavily dependent on the directed velocity, is nearly undiminished if the layer is .5 μm or less and the applied voltage is .5V or less. Also, a modest increase in voltage can make up for any energy loss. These results should apply over a wide range of doping, even up to $10^{17}/cm^3$, especially in the region where the electrons are moving fast and see a reduced ion scattering cross section.

The repercussions of the substantiation of this ballistic motion over such a wide range of thickness, temperature, and voltage will be far reaching. Ballistic electron transistors are certainly the first possibility to pursue, but other millimeter wave and high speed devices are certain to follow.

Introduction and Background

The possibility of obtaining ballistic electron motion in GaAs over substantial distances and temperature ranges was not considered feasible before our effort. The casual observer would find published characteristic electron mean free path lengths of 35 Å or so for GaAs in published avalanche analyses[1]. Although detailed Monte Carlo calculations, with the best available physical constants, were made, they approached the problem from the collision-dominated regime. At best the results, after lengthy and possibly inaccurate calculations, showed velocity "over shoot", and the cumbersomeness of the method precluded simple design by working device people. In a few such calculations,[2,3] the authors did calculate constant-electric-field effects from zero up to short distances and times, and actually plotted distance covered versus time. These plots clearly showed the distance to be proportional to the square of time, for a constant electric field. This early computer evidence of ballistic motion was not noticed, nor was the limit in energy (distance traveled times electric field) at which it ceased. One calculation[4] showed that even over long distances, cooled GaAs yielded high velocity and current in collision-dominated motion. High mobility, with low doping, was a key to this cold FET approach. The present effort was at first directed toward ballistic motion at 77°K, in an attempt to substantially improve on the cold FET approach, but as the program developed, it became clear-that the ballistic motion was not seriously diminished by going to room temperature.

By a simple power conservation argument at the threshold for Gunn effect, the author concluded some time ago that GaAs had a minimum mean free path, for low energy electrons (.05-.5V) of 1000 Å. The exact calculation is based on $(\hbar\omega_o)/\mathcal{E}_T = \lambda_{min}$, where $(\hbar\,\omega_o)$ is the polar optical phonon energy at the Raman limit (.037eV), $\mathcal{E}_T$ is the Gunn threshold electric field, and λ_{min} is the electron minimum mean free path between such collisions. The calculation of the effects of one or a few collisions showed minimal deviation from ballistic motion. Thus ballistic motion, where the (directed) electron velocity is directly determined by potential drop, was proposed as the first order effect in GaAs layers a few tenths of a micron thick. In second order, the minimal effects of collisions do cause some small velocity "undershoot", which can be theoretically and experimentally determined. It is clear that the electron energy, determined by potential drop, is now the most important independent variable, not the electric field, as was the case previously assumed for collision domination. All loses of energy by the electrons is dependent on the electron energy anyway, so that more direct calculations are also possible, when electron energy is considered the main independent variable. The remainder of this report covers the work done on this project, including an extension supported by discretionary funds on JSEP at Cornell, managed by AFOSR. The results of the development and testing of thin layers, grown by molecular beam epitaxy and without control electrodes, are presented, along with a comparison with theoretical calculations.

Report

Initial theoretical results,[5] ignoring any effects of collisions, showed a dependence of current density on the square root of bias voltage in n type GaAs when space charge injection is absent. This current density is linearly proportional to the doping. If the doping is negligibly small, and the current is carried by space-charge-limited flow, then the current density depends on the three halves power of bias voltage, as is well known from vacuum tube theory. For thin devices with low doping the latter applies, while for thicker devices with higher doping, the former applies. A transition from 1/2 to 3/2 power occurs, for intermediate cases, as the voltage rises. Later theoretical results, based empirically on earlier, possibly pessimistic Monte Carlo calculations, were also found to account for the collisions the electrons had with polar optical phonons[6,7].

While not yet published, a theory for the case of a low density of ambient acceptors has also been made, as well as the published case for ambient donors.

Several important experimental developments were necessary in order to obtain good ballistic I(V) characteristics. One is that extreme abruptness is required in the doping density drop from the heavily doped N^+ buffer layer to the very lightly doped active layer. Selenium was at first used as the dopant, using PbSe as the source in the MBE machine. While extremely high doping was obtained in the N^+ layer (mid $10^{19}/cm^3$), the system Se vapor pressure did not drop rapidly enough, so that $10^{16}/cm^3$ was as low as the doping got after .5μm growth with the Se shut off. Changing to Ge doping allowed virtually perfect abruptness, even though the N^+ layer could not be doped higher than low $10^{18}/cm^3$.

Another problem was the very low impedance of the thin active layers with high electron velocity. Any poor contact resistance is enough to swamp out the effects to be measured. Two things were done to completely avoid this problem. One was to use either state of the art alloyed contacts ($<10^{-6}$ Ωcm^2 specific contact resistance) or the new, improved MBE contact[8], developed at Cornell on an ARO contract, that yields $<10^{-7}$ Ωcm^2. This latter contact has arsenic doped Ge, with over $10^{20}/cm^3$ doping, grown epitaxially on the N^+ GaAs. When metallized, this Ge has a low barrier height (.45V), and yields a very low contact resistance without alloying. The other thing that was done to avoid this problem was to stack up five thin active layers, with thick N^+ GaAs layers between, so that the total voltage of the active layers was far greater than any across the contact.

The experimental devices were mesas, 100μm in diameter, with these five identical, stacked active layers. The contact resistance, and spreading resistance into the N^+ substrate, were determined to have a total resistance of less than .1Ω, as determined by testing the heavily Se doped layers. In order to eliminate probe resistance effects, an extra voltage probe, separate from the current probe, was used. In order to determine the doping in the active layer, a separate, semi-insulating, wafer was mounted at another position on the carousel in the MBE machine, and a Hall measurement sample was completed in the same run.

Without intentional doping, the first test wafer had five active layers, each .47 µm thick, and the ambient net acceptor density was $1 \times 10^{15}/cm^3$. The current voltage curves for 77°K and 300°K are shown in Figure 1. The total mesa voltage was divided by five to account for the five active layers in the stack, and only the voltage across one active layer is shown. Up to .3-.4 V the data could be taken C.W., and at room temperature the device was pulsed up to ~2.5 V on each active layer. The theoretical ballistic electron I(V) curves for no acceptors and for $1 \times 10^{14}/cm^3$ and $1 \times 10^{15}/cm^3$ net acceptor are shown for comparison. At low voltages the current is higher than the theoretical value, especially at room temperature, because of the initial velocity and other effects of finite temperature. At and just above .5V there is a noticeable departure from the theory, and at 1V the experimental current is only half that of the theory. At .5V the central valley of the conduction band structure has noticeable departure from a simple parabola[9]. The slope of the E(k) curve, proportional to the electron group velocity, is rising less fast at .5V, and a near saturation of this group velocity at 1×10^8 cm/s occurs. It is also reasonable to expect some electrons near the anode to transfer into the [111] and [100] direction upper valleys slowing down the average velocity somewhat. This effect may not be serious in a .5 µm device, because it takes $\sim 1 \times 10^{-13}$ secs for transfer, and in this time the electron can go .1 µm, nearly reaching the anode.

By adding just sufficient donor density, it was then possibe to over compensate the acceptors to yield 1 x 10^{15}/cm^{-3} net donors. Figure 2 shows experimental and theoretical current-voltage curves for each of these five .4 μm thick layers in the stack, with this net donor density. The theoretical prediction[5] for 1 x 10^{15}/cm^3 net donors is assymptotic to a voltage to the 1/2 power for low voltages, and approaches voltage to the 3/2 power at higher voltages. Again at .5V there begins to be a noticeable difference between the theoretical and experimental curves, and again at 1V the experimental curve is only half as high in current as the theoretical value, all for the same physical reasons as stated above. In both Figure 1 and Figure 2 the theoretical current-voltage curves under the condition of velocity saturation at 1 x 10^7 cm/s are shown for no net impurities and for the density of impurity measured in the particular layer. As can be seen, the experimental current values are many times those for the velocity saturation that would be present in thick devices.

Transistor Considerations

It now appears to be ineffective to make short gate FET devices to have full advantage of ballistic electrons. If the usual scaling up in doping is used for shorter gates, collisions with ions will tend to negate ballistic results. If the doping is scaled way down, as in the cold FET proposal, the surface depletion, as well as the depletion near the semi-insulating substrate, will be large, and the large layer thickness thus required will cause long, fringing electron paths, which in turn would lower frequency response. Ordinary surface oriented FET's would also have significant distances for electrons to travel between contacts, making ballistic effects less likely. It is thus proposed that plane, parallel closely spaced contacts be used. This could either be in a structure similar to a vertical FET, or better yet in a structure like the permeable base transistor[10,11] recently developed by Lincoln Laboratories. Figure 3 shows cross sections of both configurations. As long as the critical transit distance is held to .5 μm or less, with cathode-anode distances up to 1 μm, high ballistic velocity will yield high g_m/c for very high frequency, high speed operation. It is very likely that higher doping, even up to $10^{16}/cm^3$ - $10^{17}/cm^3$ can be used in such transistors, especially away from the negative electrode where the electron energies have built up and allow the electrons to see smaller ion scattering cross sections.

Conclusions and Recommendations

It is concluded that electrons move with very directed ballistic motion in the [100] direction in GaAs up to a peak velocity of 1×10^8 cm/s, in layers that are .5 μm or less thick, when potentials of up to .5V are applied across these thin layers. Such high ballistic velocity is obtainable at room temperature and higher, with little advantage gained from lowering the operating temperatures to 77^oK. It is further concluded that ballistic electron transistors, with the above conditions, and with a geometry like a permeable base transistor, will allow very high frequencies and speeds. This ballistic electron transistor may be only one of several new devices that can result from the ballistic electron motion.

It is recommended that fundamental and applied studies be made of such ballistic electron motion and its application to high speed, high frequency devices. Measurements of I(V) should be made in GaAs, in various crystal directions, as a function of doping and thickness. Other materials should be studied. $In_{.53}Ga_{.47}As/InP$ shows promise because of a reasonable band gap (.7V), low mass (.034 mo), reasonable minimum mean free path length (.075 μm), and large separation of lower valley (.7V). Silicon is particularly poor for this application, having only a few hundred angstroms mean free path and much lower peak velocity. Contrary to some Monte Carlo predictions, InP is also poor because of only 400 Å minimum mean free path and lower velocity. New devices, such as high speed optical detectors, and two terminal millimeter wave oscillator devices may also be possible.

Acknowledgements

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Appendix

The unpublished analysis of the current-voltage characteristic for ballistic devices with net acceptors has been made by M.S. Shur, and follows the nomenclature of the published case for net donors[5].

The normalized potential u and the normalized position w are related:

$$\sqrt{u + 2\sqrt{u}} - \ln\left(\sqrt{u + 2\sqrt{u}} + \sqrt{u} + 1\right) = \frac{w}{\sqrt{2}}$$

The value "vol" = u/u_p, and "cur" = J/J_{ch};
where

$$u_p = (eN_A L^2)/(2\varepsilon\varepsilon_o),$$

and

$$J_{ch} = (e^2 L)\left(\frac{2N_A^3}{\varepsilon\varepsilon_o m^*}\right)$$

It can also be shown that "vol" = $2u/w^2$, and "cur" = $1/w$. Relations between u, w, "vol", and "cur" have been solved in a computer. The normalizations are that $w = x/L$, and $u = (v^2 e^2 N_A^2)/J^2$, where e is electronic charge, v is electronic velocity, N_A is the net acceptor density, J is the current density, L is the device thickness, ε is the relative dielectric constant, ε_o is the free space dielectric constant, and m^* is the electron effective mass.

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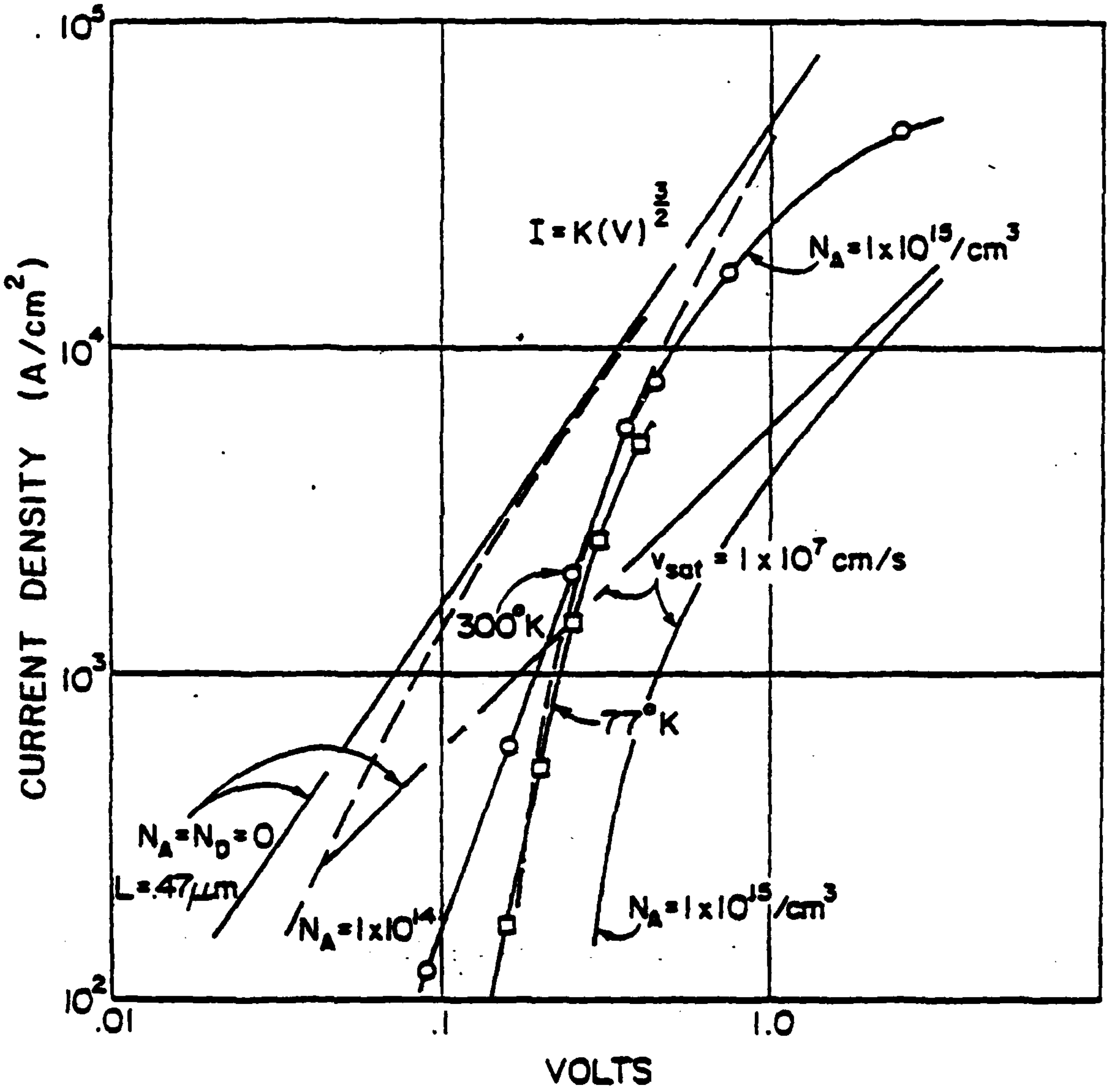
Figure Captions

1. Current density versus voltage for .47 μm thick lightly doped layer of GaAs with 1 x $10^{15}/cm^3$ net acceptors, at 300°K and 700°K. Theoretical curves of current density versus voltage for undoped, $10^{14}/cm^3$, and $10^{15}/cm^3$ under ballistic transport; and curves for $10^{15}/cm^3$ and undoped for 1 x 10^7 cm/s saturated velocity are also shown for comparison.

2. Current density versus voltage for .40 μm thick lightly doped GaAs with 1 x $10^{15}/cm^3$ net donors, at 300°K. Theoretical curves for undoped and 1 x $10^{15}/cm^3$ for ballistic transport, and curves for $10^{15}/cm^3$ and undoped for 1 x 10^7 cm/s saturated velocity are also shown for comparison. The theoretical curves for 1 x $10^{15}/cm^3$ with ballistic transport is assymptotic to a 1/2 power curve at low voltages and to a 3/2 power curve at high voltages.

3. The cross section of a single vertical ballistic electron transistor (top) and a periodic vertical ballistic electron transistor (bottom). The limit of separation of the cathode and anode is between .50 and 1.0 μm, for ballistic motion near the cathode and buried metal grid, where the device frequency response is determined.



CURRENT DENSITY (A/cm^2)
VOLTS
10^5
10^4
10^3
10^2
.01
.1
1.0
I = K(V)$^{3/2}$
N$_A$=1x10^{15}/cm^3
v$_{sat}$ = 1 x 10^7 cm/s
300°K
77°K
N$_A$=N$_D$=0
L=.47μm
N$_A$=1x10^{14}
N$_A$=1x10^{15}/cm^3

Figure 1

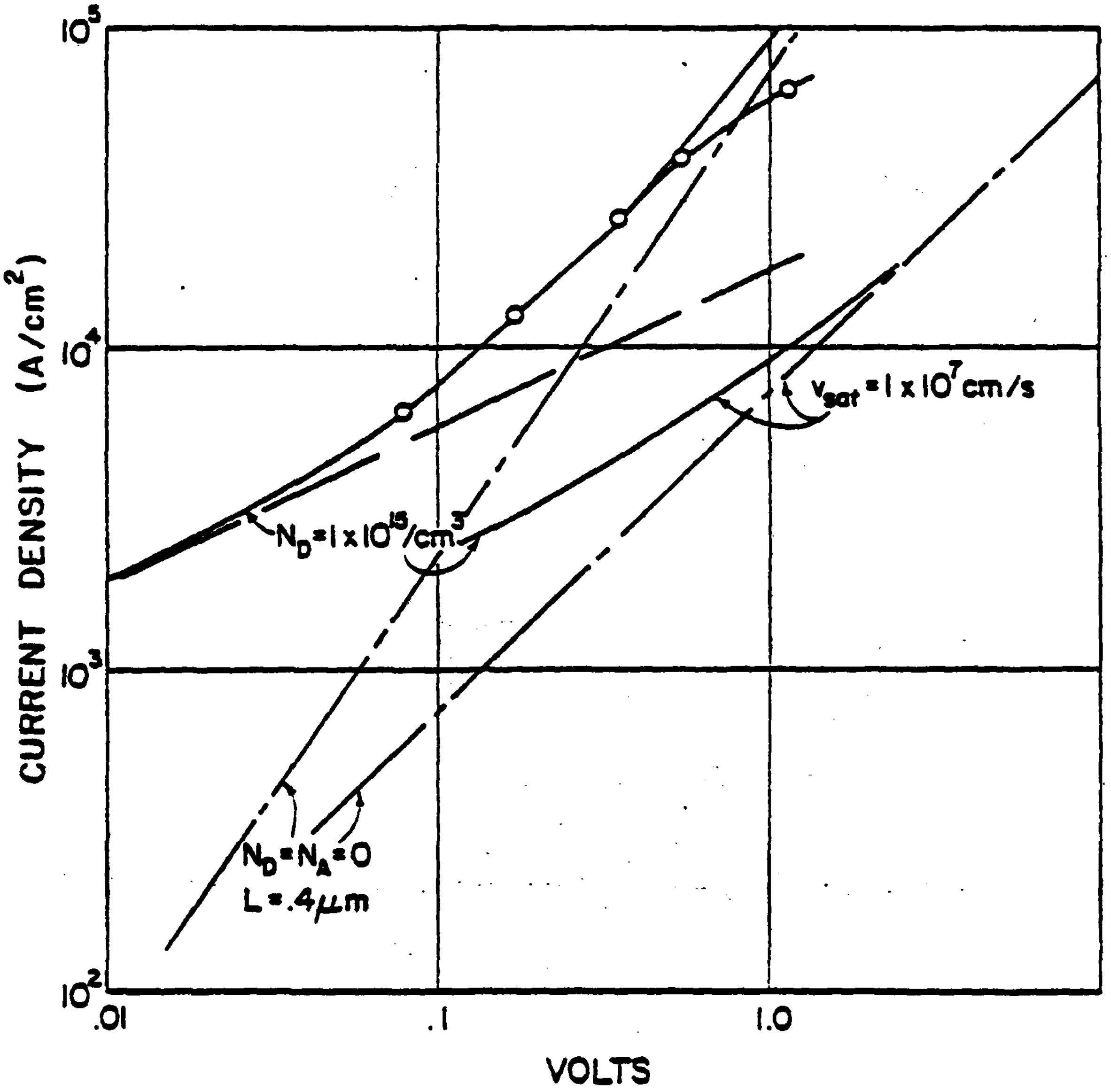

10^5
10^4
10^3
10^2
CURRENT DENSITY (A/cm^2)
.01
.1
1.0
VOLTS
$v_{sat} = 1 \times 10^7$ cm/s
$N_D = 1 \times 10^{15}$/cm^3
$N_D = N_A = 0$
L = .4 µm

Figure 2

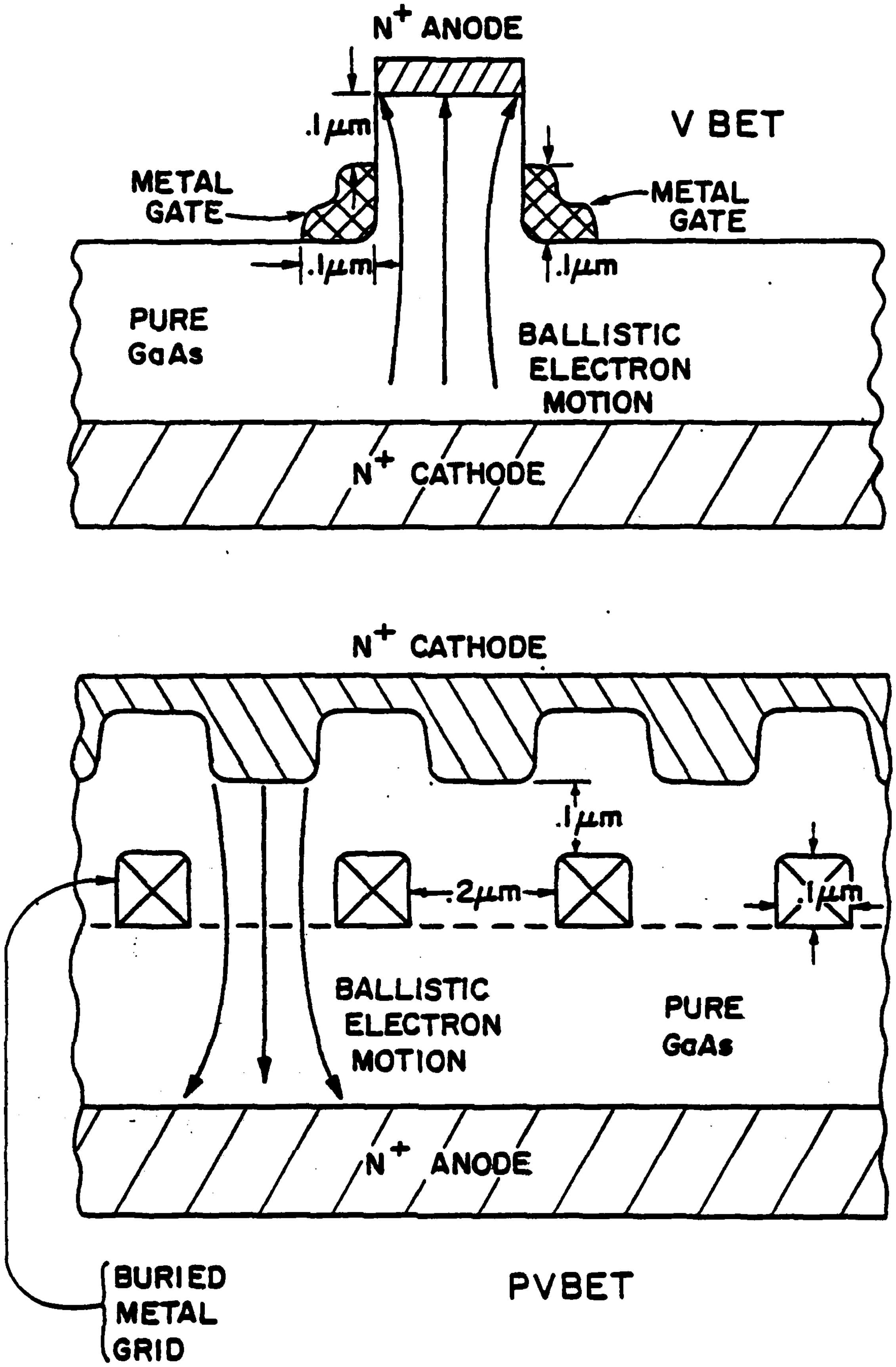

N+ ANODE
.1μm
V BET
METAL GATE
METAL GATE
.1μm
.1μm
PURE GaAs
BALLISTIC ELECTRON MOTION
N+ CATHODE
N+ CATHODE
.1μm
.2μm
.1μm
BALLISTIC ELECTRON MOTION
PURE GaAs
N+ ANODE
BURIED METAL GRID
PVBET

Figure 3

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