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EXPERIMENTAL STUDIES OF BALLISTIC TRANSPORT IN SEMICONDUCTORS

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Abstract.- The effects encountered with short-gate FET's in GaAs and In_{0.53}Ga_{0.47}As/InP show some enhancement of average velocity, but effective electrical lengths are much longer than the gates. When N^+ N N^+ short, two-terminal devices, with .36 µm electrical length, are tested at room temperature, the current density values allow one to infer an average velocity of about 4x10^7 cm/s for polarizations of 0.35 to 0.50 V.

Using Gunn effect threshold experimental data at room temperature, it will be shown that the average distance between launching polar optical phonons is just over 1000 Å at electron energy values of ≈ 0.1 eV and over 1500 Å at electron energy values of more than .3 eV; of plus the angle the plus probable after scattering is faible.

Planar doped barrier (PDB) will be presented as ballistic electron launchers and collectors, for velocity near 1x10^8 cm/s. Using closely-spaced PDB's back to back, a ballistic injection and drift condition can be set up on opposite sides of an N base region, for very high frequency transistors. By scaling the finger size to the limits of photolithography (.75 µm), over 200 GHz f_max is expected in such transistors in the near future. Using buried metal submicron base fingers, up to 1000 GHz f_max is eventually expected.

Introduction.- Substantial differences occur in the mean free paths of electrons at high and low energy in GaAs and related compounds and alloys. Analyses of avalanche phenomena, where electrons are at nearly 2.0 eV energy in GaAs, yield about 40 Å mean free path. If one applies conservation of power flow into an electron, from the applied electric field, and out away from electron, by polar optical phonon losses, much longer electron mean free paths are deduced at low electron energy from the measured Gunn effect threshold condition. The shape of the onset of polar optical phonon losses, for electron energies rising above the .037 eV polar optical phonon energy, allows a relatively low threshold electric field of 3,500 V/cm for GaAs at room temperature. When accounting approximately for the non-parabolicity of the GaAs conduction band in the (100) crystal direction, the electron group velocity is about $8 \times 10^7$ cm/s near .1 eV and rises to an asymptotic value near $1 \times 10^8$ cm/s at higher electron energy. For those electrons moving in this direction, power flow from the electric force in that direction to the electrons is simply the product of this group velocity times the force. All other electrons, moving at angles to the force, have lower rates of power flow from the electric force. A bottleneck, limiting the rise in electron energy, occurs near .1 eV where the power flows to and from the electron are equal at Gunn threshold and the power flows vs. the electron energy are tangent. At electric fields higher than the Gunn threshold value, electrons can pass through the bottleneck, always gaining more energy than they lose. Electrons must pass this bottleneck to reach .34 eV energy, where they can quickly transfer to the (111) upper valleys. Equating the two power flows, the number of polar optical phonons launched per second can be estimated at .1 eV, and knowing the electron velocity, a mean free path of just over 1000 Å is deduced. At .3 eV, where the electron velocity is higher, and the loss rate is a little lower, a mean free path of about 1500 Å is deduced. The most probable angle of scatter for electrons with .1 and .3 eV energy is just over 10° and 5° respectively, allowing a few collisions before loss of momentum occurs.

Table 1 shows the constants of some binary compounds, and ternary alloys, yielding the minimum electron mean free path for polar optical phonon launching in the last column. This length is the ratio of the polar optical energy in volts, divided by the Gunn threshold fields in volts/cm. Some of the data for InAs and related alloys are not yet known well enough, and are only estimates.

If the electrons have substantially higher rates of input power flow, a smaller and smaller fraction of the total electron energy is lost, and in the limit the rise in electron energy nearly equals the potential drop the electron has experienced. Thus the electron velocity is more dependent on potential drop than on electric field, and the electron motion is referred to as near ballistic. In the extreme case where the electron drops through a potential less than .34 eV, in a distance well below 1000 Å, energy conservation applies, and the electrons are ballistically launched at a high velocity.
When GaAs devices that are .4 and .24 μm thick are tested, high average electron velocity can be deduced from the high current density. Using $2 \times 10^{15} / \text{cm}^3$ doping and $N^+$ contact layers on both sides, tests were made of $I(V)$. Figures 1 and 2 show these curves for .4 and .24μm devices. Low mobility is expected at low electric fields for very thin devices because the thermal velocity carries the electrons quickly to the $N^+$ contacts where many collisions occur. Debye tails from the $N^+$ layers cause the electrical lengths to be reduced from .4μm to .36μm, and from .24μm to .20μm. The Gunn threshold condition is .126 V and .07 V respectively, so power losses equal gains until these voltages are exceeded on the thick and thin devices, respectively. The thick device has rising current to about .5 V, where the electron transfer energy is reached by electrons approaching the anode, in spite of an average of four polar optical phonons launched. The thin device has a faster rise in $I(V)$, especially in the .07-.40 V range, above which the electrons are able to start to transfer, in spite of the loss of two polar optical phonons, on the average. When approximate account is taken of increased space charge in the drift region, the maximum value of the average drift velocity reached is about $4 \times 10^7$ cm/s for the thicker device. Since the electron velocity rises nearly linearly in time, no more than $5 \times 10^7$ cm/s average velocity is expected when such gradual acceleration is present.

Figure 3 shows the average electron velocity versus the estimated electrical length, for some GaAs and Ga$_{47}$In$_{53}$ devices at room temperature. The change expected in the GaAs curve at 77°K is also shown. The state of the art FET, with gate length of .25μm, is shown with its effective electrical drift length of .65μm. The thicker of the above two devices is shown at .36μm electrical length and the data point at .22μm effective length represents the Bell Laboratory result where .5 ps light pulses were used to obtain $4.4 \times 10^7$ cm/s average electron drift velocity for a potential drop of .44 eV. Both of these devices had electrons moving in the (100) direction. The GaInAs devices are FET devices with .6μm gate lengths (Cornell) and effective electrical length of .8μm, and with .4μm gate length (Varian) and .6μm effective electrical length. It is evident that .44μm is the effective electrical length at which half of the total rise in average electron velocity is reached in GaAs at room temperature, as the length is shortened. This length is somewhat longer in GaAs at 77°K and in the GaInAs.

If parallel, closely spaced source and drain electrodes are used, as can be envisioned in ordinary FET's or in the permeable base transistors, then an average velocity approaching $4-4.5 \times 10^7$ cm/s could be obtained, yielding high operating frequencies.

The planar doped barrier, with its asymmetrical triangular potential variation in space, can be made to accelerate electrons to a controlled energy level in a distance much shorter than the mean free path. Figure 4 shows such a barrier in the conduction
band for different bias. In particular, electrons can be accelerated in 100-500 Å distance to a kinetic energy of .30 eV, as they flow in the forward bias direction. Because of the long mean free path, and small angle of scatter, a momentum relaxation distance of over 1μm is expected in GaAs. In a distance of .3μm, the velocity is not expected to fall below 8x10^7 cm/sec. By using two planar doped barriers, back to back and closely spaced, ballistic electrons can be emitted, allowed to drift at high speed through a base region, and be collected. Figure 5 shows this transistor potential variation in space for unbiased, and properly biased conditions.

Transistors with .15-.45μm distances between the two potential peaks have been grown by MBE. The .1-.40μm base layer has been doped from 2.5-10x10^{17}/cm^3. Built-in emitter potential drop of .3 eV, and collector potential rise of .20-.25 eV have been used. The emitter bias raises the potential peak. If this peak is higher than about .34 eV, electrons transfer to the upper valleys, even in the thinnest device, and only a .15 fraction of the emitted electrons cross the collector peak. At lower electron launch energy values, over .98 fraction of the emitted electron for .15μm drift, and over .85 fraction for .45μm drift, cross the lower energy collector peak. When the collector peak is lowered below .2 eV or so by reverse bias, thermionic emission of the base layer electrons starts to occur into the collector at room temperature. At 77°K this electron emission is sharply reduced and voltage gain near 50 can be obtained in common base operation. Further optimization of emitter and base barrier heights and shapes will allow high current and voltage gains at room temperature. Transistor operation yielding f_{max} values of over 200 GHz are expected, based on an analysis of parasitic base resistance for 1μm electrode sizes after lithography. Work on quantum reflection minimization is underway, although the gradual deceleration over distances exceeding an electron wavelength have already made such reflections small.
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$V_{PH}$</th>
<th>$E_T$</th>
<th>$M^*/M$ ($V_L - V_R$)</th>
<th>$V_G$</th>
<th>$L_{PHM}$</th>
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<td>.07</td>
<td>1.43</td>
<td>.1$^+$</td>
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<tr>
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<td>10,500</td>
<td>.08</td>
<td>1.34</td>
<td>.041</td>
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<tr>
<td>In$<em>{.53}$Ga$</em>{.47}$As</td>
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<td>2,800$^-$</td>
<td>.045</td>
<td>.75</td>
<td>.125$\mu$m</td>
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<tr>
<td>In$<em>{.52}$Al$</em>{.48}$As</td>
<td>$\sim .036$</td>
<td>3,000</td>
<td>$\sim .05$</td>
<td>1.45</td>
<td>.12$\mu$m</td>
</tr>
</tbody>
</table>

**TABLE 1**

**I-V CHARACTERISTICS**

SAMPLE $N^+N^-N^+$ GaAs

- $T=300^\circ K$
- $T=77^\circ K$

**FIGURE 1**
Current Density vs Voltage

0.24 micron n^- device

\( m = 1.25 \)

\( T = 300^\circ K \)
\( T = 77^\circ K \)
\( T = 8^\circ K \)

FIGURE 2

AVERAGE DRIFT VELOCITY

\( \text{In}_{0.53} \text{Ga}_{0.47} \text{As} 300^\circ K \)

GaAs

FIGURE 3
FIGURE 4

ACCEPOTR PLANES

CREDIT INJECTION
AND DRIFT TRANSISTOR

FIGURE 5