Current-frequency characteristics of submicrometer GaAs Schottky barrier diodes with femtofarad capacitance

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At room temperature different GaAs Schottky barrier diodes with submicrometer structure and \( \sim 1 \) fF capacitance \( C \) have been investigated in a heterodyne receiver. Using microwave sources and submillimeter lasers as the local oscillator (LO) they show that the number of electrons \( N_e \) passing through the Schottky contact each LO cycle is constant and is a characteristic value for each diode type. This is expressed by the experimentally derived equation for the optimum current \( I = N_e e / 2C \) (where \( e \) is the electronic charge and \( v \) the frequency of the radiation). The required optimum LO voltage amplitude \( V_{\text{LO}} \) is independent of operating frequency and fulfills the equation \( V_{\text{LO}} = (N_e e) / 2C \).

I. INTRODUCTION

The Schottky barrier diode as a mesoscopic system at room temperature shows under coherent radiation a current-frequency relationship similar to the nanostructured Josephson junction investigated recently by Kuzmin et al.\(^1\) It demonstrates that a constant number of electrons pass through the barrier each local oscillator cycle as seen by Kouwenhoven et al.\(^1\) in a quantum-dot.\(^2\)

The Schottky barrier diodes used in our experiments have a hexagonal structure with thousands of semiconductor-metal junctions. A tipped metal whisker provides electrical contact to the metal anode of one of the Schottky diodes, and also serves as a long wire antenna (Fig. 1). The contact between the semiconductor epilayer of highly n-doped gallium arsenide with doping levels between 1 and \( 4.5 \times 10^{17} \) cm\(^{-3} \), and the platinum anode forms a natural barrier with a thickness of \( \sim 600-1000 \) Å (see Table 1).

The Schottky barrier diodes that have recently been fabricated at the University of Virginia\(^3,4\) have submicrometer anode diameters and a capacitance of only 0.45 fF. The simplest equivalent circuit of these diodes has a nonlinear resistance that is parallel with the capacitance and in series with another resistance. (Fig. 1).

II. RESULTS FROM HETERODYNE EXPERIMENTS

The diodes are mainly used as mixers in astronomical heterodyne receivers for the submillimeter range, i.e., 100–500 \( \mu \)m/3 THz–600 GHz.\(^5\) In such a heterodyne system, they mix the coherent radiation of a local oscillator (LO) and the signal, and the resultant spectral information is converted down to lower frequencies where amplifiers and spectrometers are available. In the submillimeter range, optically pumped gas lasers with powers up to a few mW can be used as the LO source.

For these very small diodes, it is important to consider the maximum number of electrons per LO cycle that can take part in the mixing process. The behavior over the junction is altered by the LO in such a way that, within one LO cycle, electrons fill and deplete a volume \( V = AD \), where \( A \) is the anode area and \( D \) is the depletion thickness of the active mixing volume. The maximum depletion thickness \( D \) is given by the depletion thickness at zero bias which essentially is the thickness of the epitaxial layer.

Thus, the number of electrons involved is limited by the product of the doping level and the maximum possible mixing volume. Taking the data from the table for diode 1112, which has the highest doping level \( N_d = 4.5 \times 10^{17} \) cm\(^{-3} \), we end up with the quite moderate number of \( N_e = 3600 \) electrons. In recent experiments, we have found that the interaction of this fairly small number of electrons with the coherent radiation photons in a volume of submicrometer dimensions results in unusual effects. These results appear to have similarities with quantum processes that up to now have only been reported at low temperatures.

The most important parameter of a heterodyne receiver is its sensitivity, which is dominated by the performance of the Schottky barrier diode. Traditionally, the sensitivity of a Schottky diode is given in terms of mixer noise temperature \( T_{\text{mix}} \) in degrees Kelvin, which correlates the noise equivalent power \( \text{NEP}_{\text{mix}} \) of the mixer in W/Hz to an appropriate black body radiation source characterized by

\[
\text{NEP}_{\text{mix}} = k T_{\text{mix}}
\]

where \( k \) is Boltzmann’s constant. Thus, the lower the value of \( T_{\text{mix}} \) the better the mixer. The minimum mixer noise temperature for diode 1112 has been determined by experimentally optimizing the local oscillator power and the dc bias current as a function of frequency. Reference 5 discusses in more detail the optimization of the diode parameters. Figure 2(a) shows the optimum dc current through the diode when the LO power was optimized and the corresponding voltage drop \( V_{\text{eff}} \) induced by the LO power across the Schottky diode under constant current conditions.

For small area diodes, currents above 1 mA produce excessive noise and between 1.1 and 1.5 mA, the high-current density damages the Schottky contact. The uncertainty of

\[\text{footnote text: University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK.}\]
FIG. 1. Scaled cross section of a Schottky barrier diode contacted by a whisker (1112) with an enlarged view of the contact including the equivalent circuit of the junction.

$I_{\text{opt}}$ is given by the tuning range of the current within which the noise temperature is changed by less than 10%. The range of the LO voltage amplitude arises from the fact that at all frequencies of interest we have reached optimum LO power as soon as we achieve a rectified LO signal of $V_{\text{eff}} = 130-240$ mV. Thus, the bars in Fig. 2 do not represent statistical errors, but tuning ranges.

The solid line in Fig. 2(a) gives a linear relationship between optimum dc current through the diode 1112 and the operating frequency

$$I_{\text{opt}} = a \nu,$$

with $a = 3.5 \times 10^{-16} C \pm 15\%$. The constant $a$ has the dimension of a charge and corresponds to a charge of $N_e = 2200$ electrons. This shows that independent of frequency, one has to transfer 2200 electrons per LO cycle from the semiconductor to the anode to achieve optimum mixing performance for diode 1112. Thus, the active mixing volume is also independent of frequency. The resulting thickness of the active depletion region can be calculated by

$$D_{\text{depl}} = N_e / (A N_d),$$

with $A$ as the area of the Schottky diode's anode and $N_d$ as the doping level of the epitaxial layer. For diode 1112, Eq. (3) yields a value of $\sim 310$ Å for $D_{\text{depl}}$

Simply stated, $D_{\text{depl}}$ is related to the voltage drop across the barrier by

$$D_{\text{depl}} = (2 \varepsilon \varepsilon_0 N_d)^{1/2} (|V_i - kT/e - V_{\text{bias}} + V_{\text{LO}}|)^{1/2}.$$

Here, $V_i$ represents the built-in potential over the Schottky barrier, $\varepsilon \varepsilon_0$ the dielectric permittivity, $kT/e$ the average thermal voltage across the device, and $V_{\text{bias}}$ the constant bias voltage without incident laser light. Assuming $V_i$

TABLE I. Geometrical and electrical parameters of the GaAs Schottky barrier diodes used in the experiments. The capacitances are measured values.

<table>
<thead>
<tr>
<th>Diode</th>
<th>1112</th>
<th>117</th>
<th>J118</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode diameter $2R_A$</td>
<td>$0.45 \mu$m</td>
<td>$0.8 \mu$m</td>
<td>$1.0 \mu$m</td>
</tr>
<tr>
<td>Epitaxial layer thickness $D_{\text{epi}}$</td>
<td>600 Å</td>
<td>1000 Å</td>
<td>1000 Å</td>
</tr>
<tr>
<td>Depletion thickness at zero bias $D_{\text{depl}}$</td>
<td>500 Å</td>
<td>650 Å</td>
<td>~1000 Å</td>
</tr>
<tr>
<td>Epitaxial layer doping $N_D$</td>
<td>$4.5 \times 10^{17}$ cm$^{-3}$</td>
<td>$3.0 \times 10^{17}$ cm$^{-3}$</td>
<td>$1.0 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Capacity at zero bias $C_j$</td>
<td>0.45 fF</td>
<td>0.9 fF</td>
<td>1.8 fF</td>
</tr>
<tr>
<td>Series resistance $R_S$</td>
<td>33 Ω</td>
<td>13 Ω</td>
<td>30 Ω</td>
</tr>
<tr>
<td>Plasma resonance frequency at $N_D$</td>
<td>6 THz</td>
<td>5 THz</td>
<td>3 THz</td>
</tr>
</tbody>
</table>

FIG. 2. Current-frequency characteristics of the Schottky barrier diodes when used as heterodyne detectors. $I_{\text{opt}}$ is the optimum current for best mixing performance and the error bars represent the tuning range of the current without changing the sensitivity: (a) diode 1112 including optimum rectified LO voltage amplitude range $V_{\text{eff}}$ across the diode, (b) diode 117, and (c) diode J118.
As $-kT/e - V_{bias} \approx 0$ for a forward biased diode under optimum conditions, $V_{LO}$ is determined by $D_{depl}$ according to

$$V_{LO} = \frac{(D_{depl}^2 e N_d)}{2\varepsilon_{eo}}.$$  \hfill (5)

For diode 1112 with $D_{depl} = 310 \, \text{Å}$, $N_d = 4.5 \times 10^{17} \, \text{cm}^{-3}$, and $e = 13.1$ we have $V_{LO} \approx 290 \, \text{mV}$. Since we are only able to measure effective values $V_{eff}$, this number $V_{LO}$ has to be divided by $\sqrt{2}$ yielding $V_{eff} \approx 200 \, \text{mV}$ independent of the frequency of operation.

The second curve in Fig. 2(a) shows the LO voltage drop that drives the diode into the working conditions for the best performance in the coherent mixing process. The measured value of $V_{eff}$ is determined as $185 \pm 55 \, \text{mV}$. Considering the crude approximations and the uncertainty in the geometry of the Schottky barrier diode the measured and calculated values match each other quite well. The relatively high tuning range for $V_{eff}$ can be understood by considering Eq. (5), which yields a relationship $\sqrt{V_{LO}} \sim D_{depl}$. $V_{LO}$ influences the depletion range, one of the important parameters for best mixing performance very weakly.

Summarizing, the LO amplitude switches the forward biased diode between a state without a depletion layer to one with a depletion layer with a thickness of $D_{depl} \approx 310 \, \text{Å}$. Therefore, the electrons travel fast enough to respond to one with a depletion layer with a thickness of $D_{depl}$, and $e = 13.1$ we have $V_{LO} \approx 290 \, \text{mV}$. Since we are only able to measure effective values $V_{eff}$, this number $V_{LO}$ has to be divided by $\sqrt{2}$ yielding $V_{eff} \approx 200 \, \text{mV}$ independent of the frequency of operation.

Another relationship can be found by taking into account the capacitance of the active mixing region. This is approximated by the magnitude of a plate capacitor as

$$C = \varepsilon_{eo} A/D_{depl}.$$  \hfill (6)

Using $D_{depl} \approx 310 \, \text{Å}$ as it is during the mixing process, the capacitance of diode 1112 yields to $C = 0.6 \, \text{fF}$ compared to $C = 0.45 \, \text{fF}$ at zero bias (see Table I). Combining Eqs. (3), (5), and (6), one finds that

$$V_{LO} = \frac{(N_e e)}{2C}.$$  \hfill (7)

This relationship between voltage and capacitance is similar to those found in other small area junctions. Up to now, the voltage change due to the addition or reduction of just one single electron has been measured.\textsuperscript{7,8} But in our case, 2200 electrons cause the voltage drop of $V_{LO} = 290 \, \text{mV}$ over a junction with capacitance $C = 0.6 \, \text{fF}$.

In order to check the results derived for diode 1112, we have investigated two other diodes with different geometry and doping level (see Table I). Diode J118 was manufactured like diode 1112 at the University of Virginia in Charlottesville. Figures 2(b) and 2(c) show the dc current $I_{fp}$ under optimum mixing conditions as a function of frequency for these two diodes. Both diodes show a linear relationship between the optimum current and the frequency as with diode 1112. However, the slopes and therefore the number of electrons involved in the mixing process are different. For diode J117, the charge is $7 \times 10^{-16} \, \text{C}$ corresponding to $N_e = 4500$ electrons. The appropriate depletion thickness and capacitance are $D_{depl} \approx 300 \, \text{Å}$ and $C = 1.9 \, \text{fF}$. The appropriate effective voltage drop $V_{eff} = 130 \, \text{mV}$. This compares well with the voltage drop derived experimentally of $V_{eff} = 110 \, \text{mV}$.

For diode J118, the current at which the best mixing performance was achieved spread over a wide range. Therefore the linear behavior is not so pronounced. The fitted curve in Fig. 2(c) has a slope representing $\approx 2800$ electrons. This corresponds to a depletion thickness of $D_{depl} = 350 \, \text{Å}$, a capacitance of $\approx 3 \, \text{fF}$, and a voltage drop of $V_{LO} = 80 \, \text{mV}$ compared to the experimental value of $70 \pm 30 \, \text{mV}$.

### III. CONCLUSIONS

In conclusion we state that the dynamics of the mixing process in GaAs Schottky barrier diodes is governed by a very modest number of electrons. The value depends on the properties of the particular diode. The optimum current at which the best sensitivity ($\equiv$ lowest noise) will be achieved is given by

$$I_{opt} = \frac{(N_e e)}{2C}.$$  \hfill (8)

The corresponding active depletion thickness $D_{depl}$ does not vary much in the diodes investigated. So far, we do not know why $D_{depl}$ is approximately $300 \, \text{Å}$ and not significantly larger or smaller.

Heterodyne detection with a Schottky diode is a coherent process. The condition for coherence is that an electron's transverse distance through the semiconductor should be such that there should be no inelastic collisions with phonons or other electrons. In this case, the electron wave function maintains phase coherence and the electron transport is called ballistic.\textsuperscript{10,11} We have compared the experimentally determined active thickness $D_{depl}$ with characteristic lengths of the diode like the mean free path $l_f$ and the diffusion length $l_{diff}$ where $l_{diff}$ is given by the square root of the product of the diffusion coefficient $D$ and the inelastic scattering time or phase relaxation time $\tau_{sc}$. We find that both $l_f$ and $l_{diff}$ are larger than $D_{depl}$. The fact that in our case $l_f = 500-1000 \, \text{Å}$ and for the Debye length $l_D < 150 \, \text{Å}$ for the filled depletion region\textsuperscript{6} demonstrates that we have a ballistic transport of electrons through the active zone and a uniform spatial electron distribution. The different mean free path lengths arise from the doping of the different diodes. The coherency of the $N_e$ electron wave functions is forced by the coherency of the local oscillator photons. Classically speaking, $N_e$ electrons fill and deplete the active mixing area within one LO cycle. This has to be considered as a nonstationary movement of electrons in a small device length with a transient time of $t_{tr} \ll (2N_e l_{LO})^{-1}$. For the interesting frequency range 1-3 THz and the depletion thickness $D_{depl}$ this leads to typical velocities of $v_e \approx 10^7 \, \text{cm/s}$. As a drift velocity this value can be easily achieved in GaAs bulk material.\textsuperscript{9}

The above arguments show that the absolute minimum LO power required for the mixing process can be derived by assuming a "one photon input to one electron output" process. This power would be $P_{LO} = N_e h \nu^2$, which leads to

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typical values of a few microwatts for $\nu=0.7-3$ THz. The actual power required, falling on the front of the diodes, is about 100-5000× more than this. However, the overall losses are $>100$, which does suggest that the interacting LO power is not much greater than the required minimum.

The experimentally derived equations (7) and (8) indicate that when a Schottky diode with a small capacitance is driven by an external current source $I_{opt}$, it will be especially sensitive at a frequency $\nu_{LO}=I_{opt}/(N_e e)$ and amplitude $V_{LO}=(N_e e)/2C$.

These equations show a striking similarity to the basic equations of so-called Bloch-like oscillations. They have been investigated theoretically and experimentally in F capacitors, junctions, where one electron or a Cooper pair move coherently at low temperature.1,2,8,12-14 We speculate that in our case, the coherence of the LO radiation might force a larger number of electrons to move in phase in an appropriately adjusted characteristic device length $D_{dep}$ and therefore create a similar behavior even at room temperature.

So far we do not know if quantum effects play an important role in the behavior of Schottky barrier diodes irradiated with coherent laser light. If they do, they should show up as characteristic steps in either the current-voltage ($I-V$) curve or the IV curve, or both. However, we expect these steps to be very small and a very stable LO will be required if they are to be observed. We are at present developing a far infrared ring laser which should have the required stability.

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