Electrons at Schottky barrier in presence of strong coherent THz radiation

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***Abstract*—Schottky barrier diodes are widely used as mixers in THz frequency range, due to their low-noise characteristics. However, the understanding of some phenomena behind their operation is still unsatisfactory. In particular, the scaling behavior of optimal current with frequency, combined with distinct manifestations of quantum effects, which had been observed in a series of experiments, still leave a list of unanswered questions. A discussion of the latter questions, along with possible approaches to explain the experimental studies mentioned is presented, and, in particular, the possible role of the energy relaxation effects that are relevant to the phenomena under consideration is discussed.**

I. Introduction

Schottky barrier diodes used as mixers in THz frequency range are to be regarded as mesoscopic electronic devices: their small sizes in combination with their short operation times make it relevant the quantum microscopic description. A practically important examples of such devices are GaAs Schottky barrier diodes, which have been widely used as low noise mixers in high resolution heterodyne spectrometers ($\nu/\Delta\nu > 10^6$) in the spectral ranges from 300 GHz up to 5 THz (the respective wavelengths are in the range of 1 mm – 60 μm; the respective photon energies are in the range of 1.2 – 21 meV), and they have enabled a variety of applications, by using them in laboratory spectroscopy, airborne astronomy, and remote sensing with satellites [1].

The diode is generally considered to be the most critical component in the spectrometer, with respect to the receiver sensitivity. An important characteristic of this kind of electronic devices is expressed by their, so-called, noise temperature. In contrast with their well understood classical performance - in the relatively low-frequency ranges [2], certain non-classical features of the noise, and, more general, of the electron transport, develop at THz frequencies. When the diode's operation regime is optimized, with respect to the noise characteristics of the diode, a simple scaling behavior between the optimal bias current and the frequency shows up, in a wide range of these parameters [3]. Throughout the frequency range of interest, the mixing experiments with different Schottky barrier diodes have demonstrated that the best signal-to-noise ratio for these phase-sensitive detectors is achieved when the optimized depletion thickness D_{depl} for the metal-semiconductor contact fulfils the following condition:

$D_{depl}^2 = h/2e \cdot \mu = h/(2m_{eff}) \cdot \tau$,

where μ is the mobility, m_{eff} is the effective mass of the electrons, and τ is the Drude momentum relaxation or scattering time of the material, according to $\mu = e/ m_{eff} \cdot \tau$. The fact that D_{depl} is always shorter than the mean free path, and that the motion of the electrons in the mesoscopic diode contact is fast enough to respond to THz laser frequencies, leads to the following interpretation: very low scattering rates allow the electrons to maintain phase coherence, so that we have a ballistic electron transport where all electrons are moving in one direction and in phase. Moreover, for the best devices, the cooling was not necessary, with the great advantage of operating the heterodyne receivers at ambient temperature.

In addition to the relation described by the equation above, the authors of the paper cited have suggested that the best signal-to-noise ratio for Schottky barrier diode detectors is achieved with the depletion thickness being equal to twice the distance between the doping atoms, that is, $D_{depl} = 2(N_D)^{-1/3}$ (e.g., for a doping level of $N_D = 4.5 \cdot 10^{17}$ cm^{-3} the optimum depletion thickness obtained from experimental data is on the nanometer scale, $D_{depl} = 26$ nm). The two conditions described by the equations above seemingly do force electrons to move collectively and in phase, thus distinguishing such quantum dynamical characteristics of the electrons, as their de Broglie wavelengths and the Ehrenfest times.

In a more general manner, the question that may be posed here is the following: how far, on the frequency scale, the quantum limit of the classical rectifier picture for Schottky barrier diodes is? The experiments allow for the following suggestion: quantum limit is reached in the far infrared region, in a region with much lower photon energy than the band-gap energy of the semiconductor.

Though complete quantum treatment of the nonlinear non-equilibrium phenomena in a Schottky contact is impossible presently, one may nonetheless approach the problem at semi-intuitive level, combining such treatment with some simple theoretical arguments.

II. A Classical Phenomenology View on the Scaling with Frequency

A textbook equivalent circuit for a Schottky-barrier diode consists of three elements: a non-linear conductor and a non-linear capacitor in parallel, and these two in a series with a resistor, the latter being considered as a linear one. Conventional simplified Schottky barrier diode model includes a nonlinear junction IV-characteristics in the form $I(V) = I_s(\exp(V/ V_T) - 1)$, and, essentially, for not too low frequencies, a nonlinear junction capacitance in an empirical

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form $C(V) = C_0(1-V/V_1)^{-\gamma}$. The typical values of the parameter γ are close to 0.5.

In quasi-static regime, the total current through the device with the formulae above is represented by the sum

$I(V) + C(V) V'$,

and the overall voltage drop on the junction is equal to

$V + R_S (I(V) + C(V) V')$.

The IV-characteristics are thus expressed in parametric form with the depletion-region voltage-drop, $V(t)$, and its temporal derivative $V'(t)$. Such a representation is convenient to study the dynamic characteristics of the junction in terms of differential equations.

With the strong forward biasing and the large local oscillator field amplitude, there is no small parameter for the dynamics, and the only smallness is with the weak signal's amplitude: we have a periodically driven nonlinear system, which is *perturbed* by a relatively weak signal. To study the dependencies on the frequency in an *unperturbed* periodic regime the voltage drop $V(t)$ should be replaced by $V(\omega t)$, and $V'(t)$ by $\omega V'(\omega t)$. By embedding a Schottky diode into a simple circuit with some load resistance, the unperturbed dynamics may be described by a differential equation with periodic boundary condition of the following type:

$V + (R_S + R)(I(V) + \omega\, C(V) V') = E_B + E_{LO}$.

The quantity R plays a role of the load resistance, E_B represents some biasing EMF, and the EMF of the LO is represented by the $E_{LO}(t)$, which is considered to be a periodic function of time.

The optimal regime may be described as the most stable periodic regime under the condition of strongest non-linearity with respect to perturbations by weak signals. The nonlinearity of interest is assumed to be the quadratic one, for mixing. By averaging the latter equation over the LO period, and assuming that the average $\langle E_{LO}\rangle=0$, leads to the following equation for the respective averages

$\langle V\rangle + (R_S + R) \langle I\rangle = \langle E_B\rangle$,

since the average $\langle C(V)\ V'\rangle = 0$, as the average of the derivative of a periodic function. This simple result means that the frequency does not enter the averaged dynamics equation explicitly. If the function $V(\omega t)$ that represents a universal solution to the unperturbed dynamical problem, which scales with the frequency as ω^λ, then the scaling index λ may be determined using the complete equation under consideration.

To illustrate the above statements in a simple manner, a special case when $\gamma = 0.5$ exactly is analyzed in the next section.

III. $\gamma = 1/2$ APPROXIMATION

With exactly that value, the differential equation that describes the unperturbed dynamics in periodic regime may be transformed to a form, which allows for certain conclusions to be made in a rather simple manner.

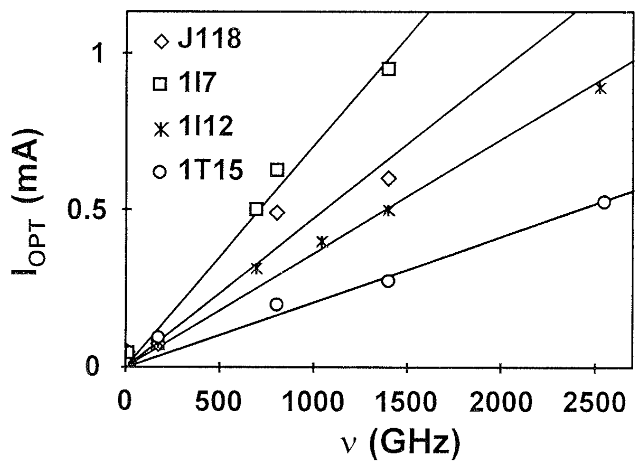
We introduce an auxiliary function $w(\omega t) = (1-V(\omega t)/V_1)^{1/2}$, and it is easy to see that it has a very simple interpretation. Since $C(V) = C_0(1-V/V_1)^{-1/2}$ does represent the (non-linear) capacitance, by comparing it with a textbook expression for the capacitance of a plate capacitor, $C = \varepsilon\, \varepsilon_0\ A\ /\ D$, the variable depletion width may be written as $D_0 w(\omega t)$, assuming that the anode area remains unchanged. Therefore, the function $w(\omega t)$ may be viewed as dimensionless variable depletion width, in the zero-voltage depletion width units, D_0.

Remarkably, the respective dimensionless equation for the depletion width dynamics takes a form resembling Riccati and Abel type equations, which fact may be useful for analytical studies.

The total current now is represented by the sum,

$-2\,\tau\,\omega\, w' + (I_s / I_{opt})\exp((V_1/ V_T)(1- w^2)) - (I_s / I_{opt})$.

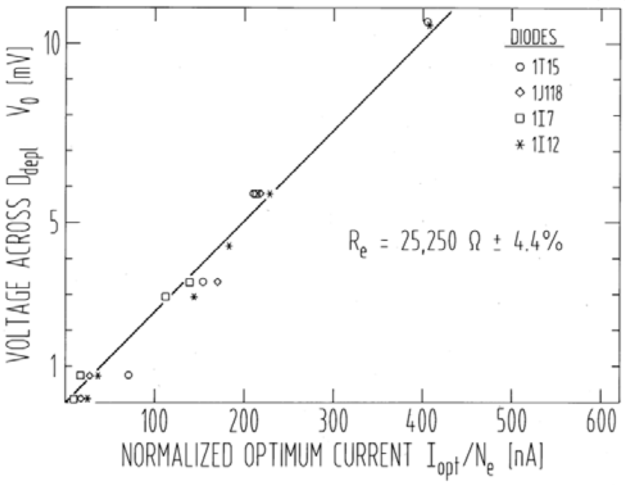
Here the characteristic time $\tau = C_0 V_1/ I_{opt}$ was introduced in this dimensionless expression, with the optimal current. With I_{opt} proportional to ω, the dimensionless quantity $\tau\,\omega$ becomes constant. Universal behavior of this kind is illustrated by examples of linear scaling of the optimal regimes with frequency in the figure below.



In general, the linear scaling behavior with LO frequency ω is not necessarily a consequence of the first-order dynamic equation, and the consideration above may be extended to other types of evolutions.

Striking feature of the model described, as compared to experimental evidence, is in that the mixer characteristics of the diode are temperature-independent despite the fact that V_T is proportional to the temperature. This may be understood as a consequence of *exponential* dependence of the resistive part of the Schottky barrier diode current on the voltage drop.

Another interesting feature of the model described in $\gamma = 1/2$ approximation consists of the universality of the solution of the differential equation, the right-hand side of which is a function of $w^2(\omega t)$; recall that D_{depl}^2 has universal meaning for a material, and that the interpretation given to the function $w(\omega t)$ is that of the variable depletion width.



Quantum-theoretical explanation of the behavior that is shown in the figure above is still lacking, and it is obvious that the complete understanding is possible only within a fully quantum picture.

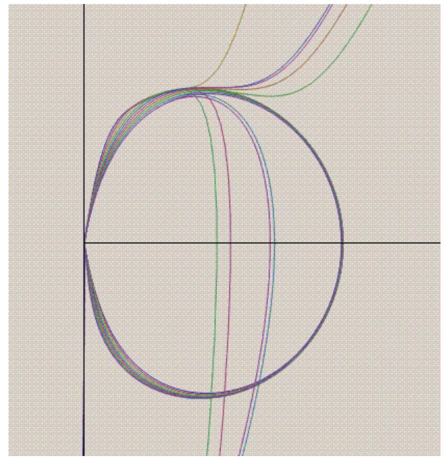
In the way of understanding that, however, another important question concerns the energy relaxation rates.

IV. Delayed response and instabilities

The optimality in the sense of the discussion presented above is closely related to the noise and stability properties in a periodically driven strongly nonlinear physical system. Though *classical* description of the system under consideration seems to be essentially incomplete, and nevertheless, in frequency regions not too high the classical approximation can be applicable. Then the energy relaxation times become comparable and longer than the temporal period of the radiation, which fact may be modeled similarly.

To advance with the model of a Schottky diode described by a differential equation, let us recall that the processes within the depletion region of the semiconductor and around that are responsible for the formation of the nonlinear response take a time to evolve, and this time is needed for the other than the voltage drop degrees of freedom. Such delays in the response of the system may be studied by using simple circuit dynamical models. Perhaps the simplest way to study theoretically the effect of delays in response formation is to include into the equivalent circuit a new element: an inductor. This element is not to be understood literally; examples of non-literal usage of such elements may be found, for instance, in nanowires [4]; the respective inductance is the *kinetic* inductance, which describes effects associated with kinetic energy of the electrons, in ballistic transport.

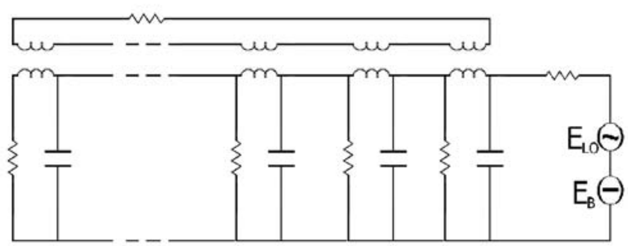
An example of the impact of the delayed reaction of the system onto its instabilities is shown in the figure below: the phase-plane $(I, I'/\omega)$ trajectories for different values of the inductance demonstrate the stabilizing role of the increased inductance; I(t) here is the resistive part of the current.



V. Modeling scaling with anode area

A question closely related to the scaling properties with respect to the LO frequency is the question of scaling with the anode area.

Traditional approach to semiconductor-based electronic devices is based on simplified one-dimensional drift-diffusion models, while the actual device operation is complicated by three-dimensional field- and charge distributions, in the presence of irreversibility effects. The effective skin depth, in the depletion region of the semiconductor, affects the effective area of the anode of the Schottky diode, and makes it frequency-dependent. The crossover within the depletion region between spatial inhomogenuities, on one hand, and the nonlinearities, on the other, are complications, which make the microscopic problem nearly intractable. In addition, of great importance are the coherence effects.



A convenient framework for modeling these types of effects are circuits like the one shown in the figure above.

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