Semiclassical description of Schottky diode mixer properties at THz frequencies

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***Abstract*— For nanostructured Schottky diode mixers being used for airborne far–infrared spectrocopy a simple semiclassical description is presented to describe their properties. Applying the Heisenberg uncertainty principle reveals the limits of this semiclassical approach.**

I. Introduction

Schottky diodes can be used as coherent detectors in high–resolution spectrometers in the THz frequency range. The Schottky diodes serve as low–noise mixers and permit the detection of weak signals, for example from cold interstellar clouds, with a high spectral resolution of $10^6 - 10^7$ with a bandwidth of several GHz [1].
An important feature of Schottky diodes is that they need not necessarily be cooled down to cryogenic temperatures when being used as coherent detectors and that they perform with high sensitivity even at room temperature.
Requiring no cryogenic cooling leads to enormous advantages with regard to energy consumption and system weight. Hence, using Schottky diodes as heterodyne detectors is of great interest for air– and spaceborne astronomical and Earth observation missions.
Schottky diode mixers based on gallium arsenide have been employed successfully for airborne FIR astronomy for many years. The quasi–optical setup of a detector block is shown in the figures 1 and 2.

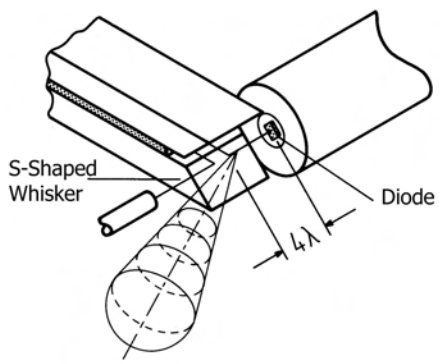

Fig. 1. Schematic drawing of the quasi–optical mixer block with signal beam, 90°–reflector, whisker antenna and diode chip

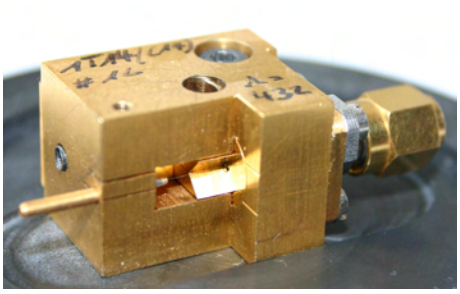

Fig. 2. Photo of a quasi–optical detector block

During the preparing, optimizing and qualifying for flight experiments, many measurement data were taken. The re–investigation of these data revealed the following relationships under room temperature conditions without external magnetic fields, with only the local oscillator illuminating the detector antenna, and for optimum mixing and best signal–to–noise ratio [2], [3]:

1. The net current through the depletion layer of the Schottky contact is proportional to the frequency of the local oscillator. The proportionality constant can be interpreted as the number of electrons being transported through the depletion layer per local oscillator cycle times the electric elementary charge e:

$$I = N_e \, e \, \nu \tag{1}$$

2. The square of the depletion layer thickness is proportional to the electron mobility in the semiconductor material. The proportionality constant is the magnetic flux quantum $h/2e$:

$$D_{depl}^2 = \frac{h}{2\,e}\,\mu \tag{2}$$

3. The resistivity is proportional to the number of electrons being transported through the depletion layer per local oscillator cycle. The proportionality constant is the quantum hall resistivity h/e^2:

$$R = \frac{h}{e^2}\,\frac{1}{N_e} \tag{3}$$

4. The current density in the depletion layer reaches up to $10^6 A/cm^2$.

II. Semiclassical model

One can describe the functioning of the Schottky diode mixer via a modified Millikan–type experiment: A laser beam ($h\nu$) is incident on a cathode which is acting as a photon detector, see figure 3. The electrons travel from the cathode to the anode, whereby the cathode and the anode are acting like a capacitor. The geometry of this capacitor is given by its thickness, which is defined by the depletion layer thickness D_{depl}, and by its diameter, which is defined by the whisker contact diameter $\varnothing_A$. The capacitor is filled with semiconducting material.

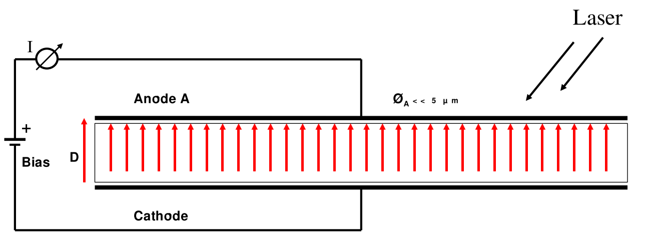

Fig. 3. A Millikan–type experiment with a semiconductor between anode and cathode

A semiclassical description can be achieved through an equation describing the photoelectric effect for one electron

$$e\,V_0 = h\,\nu - \frac{e^2}{2\,C}\ , \tag{4}$$

where $\dfrac{e^2}{2\,C}$ replaces the work function in Millikan's experiment with the energy change that the electron undergoes when traveling from the cathode to the anode.

Assuming that $h\,\nu >> \dfrac{e^2}{2\,C}$ (which is valid for the diode operating envelopes), and with $V_0 = R\,I$, one gets

$$R = \frac{h}{e^2} \tag{5}$$

for one electron. Assuming that all N_e electrons are travelling in parallel, the resistance finally becomes

$$R = \frac{h}{e^2}\,\frac{1}{N_e}\ . \tag{6}$$

If one assumes that the diode acts like a velocity filter such that

$$v = \mu\,E = \mu\frac{V_0}{D_{depl}} = 2\,D_{depl}\,\nu\ , \tag{7}$$

the result

$$D_{depl}^2 = \frac{h}{2\,e}\mu \tag{8}$$

is evident. Equation 7 requires that the transport of charge takes place during half the laser cycle time $\dfrac{1}{\nu}$.

In table I, the contact diameter $\varnothing_A$, the depletion layer thickness D_{depl}, the mean free path of the electrons λ_e, the number of electrons being transported per laser cycle N_e, the electron mobility μ and the doping level N_D for diodes with different geometries are listed.

TABLE I

Data for different diodes I

Diode	J118	1I17	1I12	1T15
$\varnothing_A$ [nm]	1000	800	450	250
D_{depl} [nm]	32	27	26	21
λ_e [nm]	84	64	52	35
N_e [-]	2800	4500	2200	1300
μ [cm^2/(V s)]	5000	3600	3100	2100
N_D [10^{23}/m^3]	1.0	3.0	4.5	10.0

Obviously, the electron transport through the depletion layer is ballistic because the mean free path is roughly twice as large as the depletion layer thickness for all diodes.

III. Limits of the semiclassical model

1. From the data given in table I it is possible to calculate the number

$$N_{cc} = \varnothing^2\,\frac{\pi}{4}\,N_D^{2/3} \tag{9}$$

which is an estimation of the number of doping atoms in a plane layer perpendicular to the direction of the current transport. Comparing N_{cc} (see table II) with N_e, one can say roughly that

$$N_e \approx 2\,N_{cc}\ , \tag{10}$$

so that one could speculate that the number N_{cc} denotes the number of current channels defined by the crystal structure where 2 electrons travel through during each laser cycle time $1/\nu$. It is an open question whether the electrons behave like Cooper pairs interacting with the laser photons.

It is also interesting to calculate the number

$$N_{dd} = D_{depl}\,N_D^{1/3} \tag{11}$$

which is also tabulated in table II. This reveals that $N_{dd} + 1 \approx 3$ doping atoms apparently make up one current channel in the direction of the current transport. This raises the question if and how the crystal (and hence, charge) structure influences the electron transport.

The de Broglie wavelength for an individual electron is defined by

$$\lambda_{dB} = \frac{h}{m_e^*\,v}\ . \tag{12}$$

The velocity v shall be estimated here by

$$v = D_{depl}\cdot 1\,THz \tag{13}$$

because $1\,THz$ is the typical laser frequency. The values (table II) show that $\lambda_{dB} >> D_{depl}$. Hence, the wave–like behaviour of the electrons and a confinement effect certainly play an important, role which has to be explained. In addition, once one starts regarding the wave–like behaviour of the electrons, the question is raised if all electrons N_e behave in a coherent manner.

Appplying Heisenberg's uncertainty principle in the current direction

$$\Delta x \, \Delta p_x \geq \frac{\hbar}{2} \,, \tag{14}$$

with $\Delta x = D_{depl}$ and $p_x = m_e^* \, v$, one gets the uncertainty of the velocity

$$\Delta v_x \geq \frac{\hbar}{2} \frac{1}{D_{depl}} \frac{1}{m_e^*} \tag{15}$$

which is listed in table II. The uncertainty of the velocity is of the same order like the estimated velocity v which raises the question how correct it is in the semiclassical description to talk about a velocity filter mechanism of the diodes.

Applying Heisenberg's uncertainty principle in the direction perpendicular to the current direction and assuming that the initial uncertainty is $N_D^{1/3}$, the uncertainty is calculated as

$$\Delta y \geq \frac{\hbar}{2} \frac{1}{m_e^*} N_D^{1/3} \frac{1}{\nu} \tag{16}$$

which is also tabulated in table II. The values for Δy are of the same order like D_{depl}.
With $N_D^{-1/3}$ representing the distance between the above mentioned current channels, it becomes clear that it is not possible to assign one electron (or an additional one due to equation 10) to one current channel, because its uncertainty Δy due to the Heisenberg principle is bigger than $N_D^{-1/3}$.

Hence, the processes involved in the electron transport through the nanoscale Schottky barrier have to investigated further by using the more fundamental principles of quantum electrodynamics. This is also highlighted by the fact that the wavelength of the laser photons is way bigger than the device structure so that it also remains an open question where and how photons and electrons interact.

TABLE II
DATA FOR DIFFERENT DIODES II

Diode	J118	1I17	1I12	1T15
N_{cc} [-]	1692	2253	933	490
N_{dd} [-]	1.5	1.8	2.0	2.1
v [km/s] (1 THz)	32	27	26	21
λ_{dB} [nm] (1 THz)	361	428	444	550
Δv_x [km/s]	29	34	35	44
Δy [nm] (1 THz)	43	62	70	92
$N_D^{-1/3}$ [nm]	22	15	13	10

IV. CONCLUSION

A Millikan–type photoelectric effect equation and the concept of a velocity filter allow a semiclassical description of the properties of Schottky diodes being used as heterodyne mixers for FIR astronomy. Some simple calculations of the crystal lattice structure and the application of Heisenberg's uncertainty principle reveal some astonishing new questions that need to be answered in the future. We have decided to attack these questions via a direct simulation on the basis of quantum electrodynamics.

REFERENCES

[1] H.–P. Röser, H.–W. Hübers, "Schottky barrier devices for THz applications," *in: J.M. Chamberlain, R.E. Miles (eds.): New Directions in Terahertz Technology, NATO ASI Series E: Applied Sciences, Vol. 334, Kluwer Academic Publishers,* 1997.

[2] H.–P. Röser, H.–W. Hübers, E. Bründermann, M.F. Kimmitt, "Observation of mesoscopic effects in Schottky diodes at 300 K when used as mixers at THz frequencies," *Semicond. Sci. Technol. 11, pp. 1328—1332,* 1996.

[3] H.–P. Röser, H.–W. Hübers, "Mesoscopic effects in nanostructured GaAs Schottky detectors," *IRMMW 2001, pp. 2-46–2-49, ISBN 2-87649-035-8,* 2001.