RESPONSE OF TUNNEL SCHOTTKY-BARRIER JUNCTIONS TO RADIATION PRESSURE OF FIR LASER RADIATION

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Abstract

The response of tunnel Schottky junctions due to plasma reflection of laser radiation has been investigated in the far infrared. The signal was found to be independent of the laser radiation frequency below the plasma edge. At high power levels a nonlinearity of the response was observed. It is assumed that this nonlinearity is caused by near-zone field effects which lead also to a substantial enhancement of the responsivity.

1   Introduction

The resistance of tunnel metal-semiconductor junction is very sensitive to the shape of the Schottky-barrier self-consistent potential [1, 2]. This potential is formed by the charges of ionized impurities located in the depletion layer of the semiconductor, by the charge on the surface states in the semiconductor-metal interface, and by free electron screening. As a result, the equilibrium position

of the boundary of the free electron plasma in the semiconductor determines the thickness of the Schottky barrier. Thus the tunnel resistance is affected by an external force applied to the electron plasma. Such a force may be produced by the light pressure arising at total reflection of radiation with frequencies below the plasma edge of the semiconductor. In previous studies of tunnel Schottky-barrier junctions a fast photoresistive response to pulsed FIR laser radiation has been observed [3]. It was shown that the plasma reflection condition is essential to obtain the fast response. Several other qualitative and semi-quantitative tests and comparisons between experimental data and theoretical model calculations have been carried out [4]. The results allowed to exclude free electron heating due to absorption of radiation as a cause of the observed signals. Here we present response measurements on $n - GaAs/Au$ tunnel junctions in a wide range of intensity for various far-infrared wavelengths yielding more insight in the mechanism of signal generation. At high intensities a superlinear increase of the signal with rising intensity has been observed for the first time. This allows to conclude on a radiation field enhancement in the near-field zone at the metal-semiconductor interface.

2   Experimental Technique and Results

The investigations have been carried out $n - GaAs$ tunnel junctions with plasma reflection minimum near 20 μm wavelength. The diodes where prepared with semitransparent gold films of about 20 nm thickness as electrodes having a diameter of 1 mm. On top of each contact an opaque aluminum blind was fixed which left a hole of 0.5 mm^2 open area for irradiation. The photoresistive response has been measured as a function of radiation intensity and FIR wavelength. The measurements were carried out using a $TEA - CO_2$ laser-pumped high power FIR molecular laser. Laser lines with wavelengths 76 μm, 90.5 μm, 152 μm, 385 μm and 496 μm were applied within an intensity range of 5 kW/cm^2 up to 1 MW/cm^2 and duration of the radiation pulses of the order of 100 ns.

In order to obtain reliable data for the radiation intensity, the geometrical profiles of the spatial distribution of the laser beam

near the focus of the optical system were measured by means of the same tunnel junctions under study. Fig. 1 shows the beam
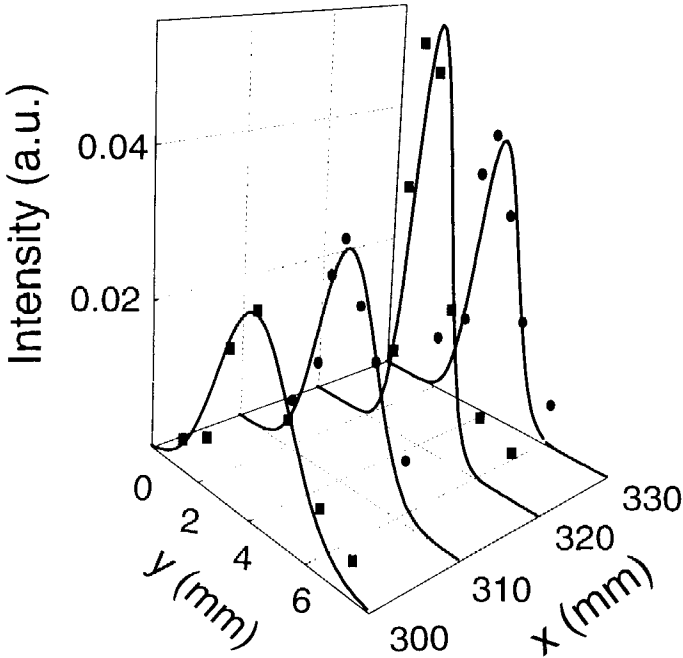

Figure 1: *The spatial beam structure* (λ = 90.5 μm) *for differ-ent distances from a parabolic mirror with focal length of 320 mm. The intensity is measured by a tunnel Schottky-barrier junction $n - GaAs/Au$ at T = 300 K with a diameter of 0.5 mm. Solid lines are calculations of the Gaussian beam fitted to experimental data.*

profile for λ = 90.5 μm along the propagation direction x close to the focal spot at x = 320 mm of a parabolic mirror of 320 mm focal length. In Fig. 2 the spatial intensity distribution is plotted for λ = 250 μm in the focal plane of the same parabolic mirror.

In Fig. 3 the tunnel-junction signal is shown as a function of FIR intensity for the various wavelengths. The response depends linearly on intensity J up to $200 - 500$ kW/cm^2. At higher inten-sities a deviation of linearity is observed. Fig. 3 also shows that

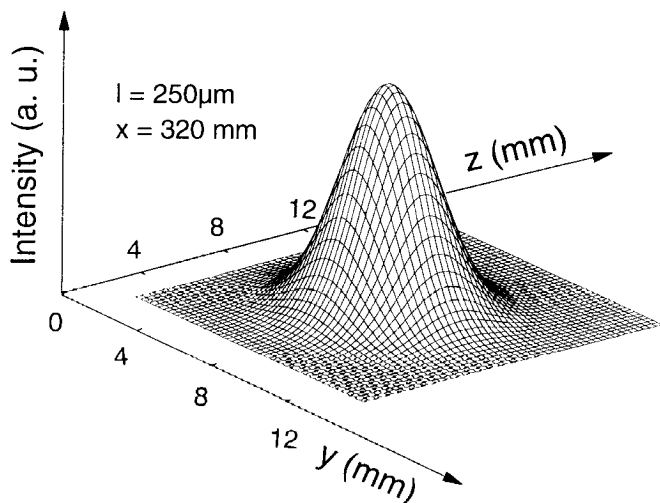Figure 2: *Calculated spatial beam structure in the focal plane of a parabolic mirror with a focal length of 320 mm for $\lambda = 250 \ \mu m$. The calculations have been fitted to two dimensional spatially resolved measurements with a tunnel Schottky-barrier junction $n - GaAs/Au$ at $T = 300 \ K$ having a diameter of 0.5 mm.*

the response is independent of the wavelength in a wide spectral range. The response time of the investigated tunnel junctions was about 10 *ns*. This time is determined by the area of the contacts and may be further decreased by reducing the contact size.

3   Discussion

The independence of the signal on wavelength and the linearity of the response at low intensities, are in agreement with theory taking into account the redistribution of free electrons at the plasma boundary caused by the ponderomotive force [4]. This force is assumed to be produced by the evanescent electromagnetic wave during the plasma reflection. The observed magnitude of the signal, however, is about 50 and 16 times higher than given by theoretical estimations for positive and negative bias voltages, respectively.
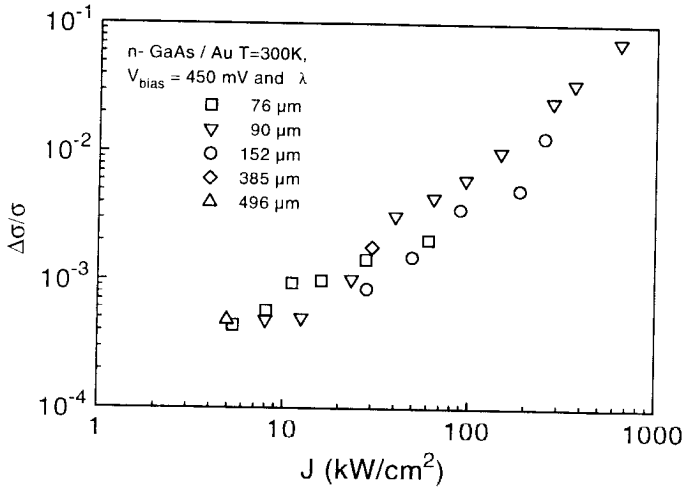
Figure 3: *Relative photoconductive signal $\Delta\sigma/\sigma$ as a function of the incident radiation intensity J for different wavelengths. Results are plotted for a tunnel Schottky-barrier junction $n - GaAs/Au$ at $T = 300\,K$ with positive bias voltage $V_{bias} = 450mV$.*

One of the reasons of this discrepancy could be the local enhancement of the incident wave field near the irradiated surface of the semiconductor. Such an enhancement of the radiation field has been observed, for example, in giant Raman scattering by adatoms on rough metal surfaces [5] where an increase of the scattering intensity by a factor of $10^4 - 10^5$ was found. Similar effects occur in the case of second harmonic generation by metal surfaces [6]. The source of this enhancement is related to inhomogeneities at the metal surface which favours the generation of surface polaritons or plasmons by the incident radiation even if the angle of incidence is zero (see for instance [7], p 485 and Fig. 4 in [8]). In our case the inhomogeneities may be due to the non-uniformity of the thickness of the semitransparent gold film evaporated on the $GaAs$ surface. It is known, that gold films on $GaAs$ have usually an island structure at thicknesses $\leq 8\ nm$ and become homogeneous for thicker films. The Au electrodes of the present tunnel junctions with a thickness

of about $15 - 20$ nm provide a good conductivity and do not exceed the thickness of the skin layer in the range of radiation frequencies being of interest here. The films have been shown to be transparent for visible light which was proved by the observation of a barrier photovoltaic effect induced by $He - Ne$ laser radiation. In addition measurements of the free carrier absorption of $10\mu m$ radiation transmitted through the Au electrodes revealed that the attenuation of the radiation at this wavelength does not exceed 50 percents. Thus for longer wavelength radiation in the far infrared range the transmittance of the Au electrodes should be even higher.

The thickness of the electrodes is very close to that of the transition from the island structure of the deposited film to a homogeneous film. Therefore the films may be nonuniform in thickness and transparency for incident radiation. This could lead to an enhancement of the effective field because of the high near-zone field strength similarly to the case of scattering of radiation by an aperture in a conducting screen (see, for example, relations (13) - (14) in [9]). Such a mechanism may also be responsible for a surface enhancement of the local field which affects the transparency of the tunnel Schottky barrier. On the other hand, surface plasmons must be ruled out because they have a component of the electric field perpendicular to the surface which would enter the Maxwell stress tensor with opposite sign compared to the transverse components. In this case the sign of the signal should be opposite to the observed one (see Eq. $(4.5a)$ in [4]).

Here we would like to show that the deviation of the response as a function of intensity from linearity at high intensity levels supports the view that near-zone field enhancement of the radiation field strength significantly stimulates the tunneling process. The nonlinear dependence $\Delta\sigma/\sigma$ on J allows to determine the absolute magnitude of the electromagnetic field strength in the depletion layer of the Schottky barrier. This will be shown by modifications of the expression for the response of a tunnel junction to the radiation pressure previously derived by us [4].

The tunnel current I is given by:

$$I \propto \int_0^\infty dE \left[f(E) - f(E + eV) \right] \exp\left(-G\right), \tag{1}$$

where G is in the quasiclassical approximation:

$$
\begin{aligned}
G(E, \Phi_b, u) &\equiv \frac{2(2m)^{1/2}}{\hbar} \int_{x(E,u)}^{0} dx \, [\Phi(x, u) - E]^{1/2} = \\
&= \frac{2(2m)^{1/2}}{\hbar} \int_{E}^{\Phi_b} d\Phi \frac{(\Phi - E)^{1/2}}{\Phi'} = \\
&= \frac{2\mu}{\hbar \omega_p} \int_{\varepsilon}^{W_b} dw \left(\frac{w - \varepsilon}{w - 2/5 + K_e u/\mu} \right)^{1/2}
\end{aligned} \tag{2}
$$

In this equation $f(E)$ is the electron distribution function as a function of the energy E, m is the effective mass of electrons, $\Phi(x)$ is the potential electron energy in the barrier, $x(E, u)$ is the classical turning point of an electron with energy E in the barrier disturbed by electromagnetic field, $\Phi_b = \Phi_s + \mu - eV$ is the band bending at the semiconductor-metal interface, Φ_s is the surface barrier height, V is the bias voltage that is taken to be positive as the electrons tunnel from the semiconductor to metal film, $\Phi'(x) \equiv \partial\Phi/\partial x$ is proportional to the static electric field in the barrier, ω_p is the plasma frequency of the electrons, and u is the high frequency potential [10] produced by the reflected electromagnetic wave in the depletion layer of the Schottky barrier. If the usual Fresnel boundary conditions are applied to the semiconductor-vacuum interface then u is related to the intensity of the incident radiation as:

$$
u \equiv e^2 \left| \mathcal{E}_\infty \right|^2 / 4m\omega^2 = J/N_e c, \tag{3}
$$

where $\mathcal{E}_\infty$ is the complex amplitude of the electromagnetic field in the depletion layer, ω is the radiation frequency, J is the intensity of incident radiation, N_e is the bulk density of free electrons, and c is the velocity of light in vacuum. The last line in Eq.(2) is written in dimensionless variables $w = \Phi/\mu$ and $\varepsilon = E/\mu$, where μ is the Fermi energy of the electrons in the semiconductor. Now we can write the expression for the response allowing to study the nonlinear region:

$$
\frac{\Delta\sigma}{\sigma}\bigg|_{V=const} = \frac{\Delta I}{I}\bigg|_{V=const} = \frac{\eta \left[I(V, u) - I(V, 0) \right]}{I(V, 0)}, \tag{4}
$$

where η is a normalizing factor which has been used to fit the

calculations to the response measured at small intensities in the linear regime.

The electric field enhancement at the surface of the semiconductor has been introduced in Eqs. (1) and (2) by assuming a factor K_e (see Eq. (2), last line). The results of the calculations of the response for various values K_e and η are presented in Fig. 4 together with experimental data for the wavelength of 90.5 μm. It is seen that using a single factor $K_e = 10^4$ permits to describe the nonlinearity of the response for both positive and negative biases. Calculations with other K_e shown in Fig. 4 demonstrate that the response as a function of J sensitively depends on this field enhancement factor.

The normalizing factor η in Eq. (4) linearly scales the magnitude of the signal $\Delta\sigma/\sigma$ and does not change the intensity dependence. As described above without field enhancement, i.e. $K_e = 1$, the observed signal was larger than the calculated one which corresponds to $\eta = 50$ for positive bias and $\eta = 16$ for negative bias (see Fig. 4). Taking into account the field enhancement such that the nonlinear intensity dependence is correctly described, normalizing factors $\eta = 1/200$ and $\eta = 1/600$, respectively, are needed to get a quantitative agreement to the measurements.

Indeed this normalizing factor should reflect the relation between the area where the field enhancement occurs and the area of the whole Au electrode where the dc tunnel current flows. The difference of η for both biasing conditions may be due to neglecting in the calculation the contribution of the electron states below of the Fermi level to the tunnel current at positive bias (see for more details [4]). However, it is seen from Fig. 4 that the ratio between η for positive and negative bias is independent of the enhancement factor K_e, and therefore this difference is not important for the evaluation of the enhancement factor.

Due to the fact that the tunneling current rises exponentially with increasing the field enhancement coefficient K_e, only the part of the contact area, where K_e is substantially larger than one, yields the major contribution to the response. The effective diameter of this area is thus the total diameter of the electrode multiplied by $\eta^{1/2}$. With the above value of $\eta = 1/600$ for negative bias which is more reliable we find for this diameter the value about $40\mu m$. This is somewhat less than but still of the order of the radiation wavelength
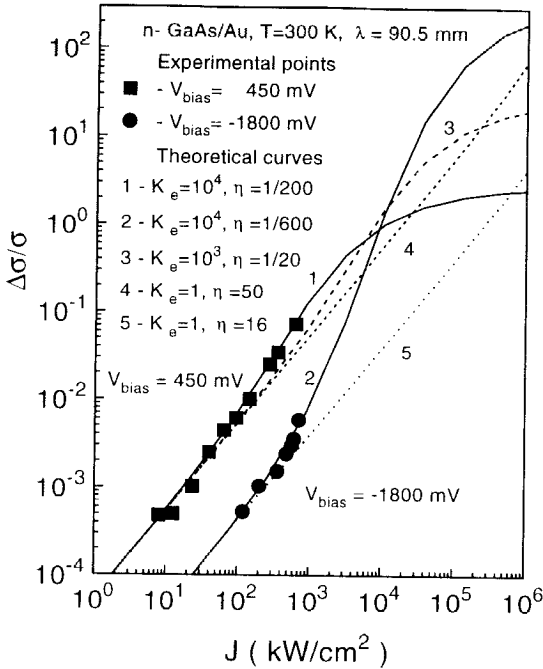
Figure 1: *Relative response $\Delta\sigma/\sigma$ as a function of the radiation intensity J. Squares and circles are measurements for the positive and the negative bias voltage V_{bias}, respectively. Lines are calculations after Eq. (4) for different enhancement factors, K_e, and normalizing factors, η. Lines 1, 3, 4 correspond to the positive bias, lines 2 and 5 to the negative bias. The semiconductor parameters used for calculations are: $N_r = 2 \cdot 10^{18} cm^{-3}$, $\Phi_s = 0.9\ eV$.*

being $90.5\mu m$ and agrees well with the initial assumption of edge or small aperture effects on the radiation field.

Finally we would like to note that near-field effects may also arise due to a component of the electric field normal to the metal-semiconductor interface. Such a component might appear because of diffraction of the incident electromagnetic field on the effective electrode area. Recently, the Bethe problem [11] of the near-field distribution of diffraction at a small aperture was analytically solved for

the case of normally incident radiation [9]. However, the result shows that the electric field perpendicular to the semiconductor surface in the vicinity of the illuminated Schottky junction should be negligible in the region of the Schottky barrier. Nevertheless, a significant enhancement of the transverse electric field should occur near the aperture edge. Such a structure of the field inside the aperture justifies the applications of the expressions derived in [4] for the case of a pure transverse field of the incident wave.

4   Conclusion

In summary, the dependence of the tunnel junction response on λ and J has been investigated in far-infrared region. The comparison with theoretical calculations indicates the importance of the effects of the enhancement of the radiation field near the semiconductor-metal interface. The investigations demonstrate the potential application of tunnel Schottky diodes as wavelength independent devices to detect FIR laser pulses. The response was found to be linear up to 100 kW/cm^2. The observed near-zone field effects show that the sensitivity of detection may considerably be improved compared to plain tunneling diodes by proper preparation of the metal electrodes. The time constant of detection may be significantly reduced by down-sizing the area of the junctions up to several μm^2. Subnanosecond time constants seem to be possible. Furthermore by existing technology a large number of junctions may be monolithically integrated yielding a two dimensional array for laser beam profile analysis with high temporal resolution. In addition, a small semiconductor needle with a Schottky contact on its tip may be useful for near field detection as well (see, for instance [12] and references therein).

Acknowledgement

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