Reassessing Plasma Resonance in THz Detection: Energy Losses of Carriers in Field-Effect Transistors

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The conditions required for the generation of surface plasmons at the dielectric–semiconductor interface are crucial for evaluating the suitability of the plasmon model for the description of THz detection using field-effect transistors. Existing literature often simplifies the plasma resonance formula, neglecting energy losses of free carriers, which is especially problematic near the threshold voltage regime of transistors. In this paper, we show that an insufficient number of free carriers in this regime prevents the plasmon formation in wideband semiconductors at room temperature, which challenges the validity of the plasmon model under these conditions.

topics: terahertz (THz) radiation, THz detection modeling, surface plasmons, field effect transistors

1. Introduction

The plasmon model of THz detection using high-electron-mobility transistors (HEMTs), published by Dyakonov and Shur in 1996 [1], has been influential in explaining the THz radiation detection, on frequencies far exceeding the characteristic transistor frequencies (e.g., cut-off) predicted by the drift–diffusion model of electron transport. Over the following decades, the plasmon model was used to explain the THz detection observed in a variety of n-type field-effect transistors (FETs). However, it is important to note that this model did not explain the significant THz detection observed in p-channel transistors [2], where holes serve as charge carriers. Notably, plasmonic phenomena have never been experimentally observed for a free-hole gas. Holes in semiconductors have insufficient mobility even at cryogenic temperatures, which makes it virtually impossible for plasmonic effects to occur. In this article, we discuss a fundamental limitation of the model of plasmon-related detection, namely the necessity for a sufficient number of free carriers to balance the polarization caused by the lattice-bound electrons in semiconductor materials.

2. Justification

At very high (optical) frequencies, the free carriers in semiconductors fail to keep up with the rapid electric field changes, causing the semiconductor to behave more like a dielectric. The bound electrons then dominate the material's polarizability. The properties of the semiconductor for this range are described by a constant (real) value of the dielectric function $\varepsilon_{\mathrm{core}}$ (often denoted as $\varepsilon_{\mathrm{opt}}$), which is almost independent of the angular frequency ω. As the frequency decreases, the free carriers in the semiconductor begin to follow the electromagnetic field (EM), reducing the contribution of the bound electrons to the overall polarization. This change occurs gradually and is observable at room temperature in heavily doped n-type semiconductors or those with low effective electron masses (e.g., InSb). The effect is typically measured through the reflection coefficient of an electromagnetic wave as a function of its wavelength. For semiconductors with relatively large effective carrier masses (such as silicon or gallium arsenide), this effect becomes visible at cryogenic temperatures, where the carrier mobility increases, allowing the material to respond more effectively to high-frequency electromagnetic fields. A corresponding experiment was described for a silicon n-type FET at liquid helium temperature [3].

We explore important consequences of accounting for free carrier losses (due to scattering and other interactions) on the plasma resonance frequency. This article does not address ballistic transport typical of deep submicron devices. The derivation of the formula for plasma resonance frequency was taken from a widely appreciated textbook [4], preserving the original symbols of variables. The formulas are supplemented with appropriate comments.

The plasma resonance frequency ω_p is the frequency near which a semiconductor transitions from dielectric to metallic behavior. It is the frequency at which the real part of the complex dielectric function equals zero and the polarizability of bound electrons is balanced by the influence of the semiconductor's free carriers. The complex dielectric function $\varepsilon(\omega)$ and the complex electrical conductivity $\sigma(\omega)$ together with the complex magnetic permeability are functions that relate the properties of a material to its response to a changing EM field. Using Maxwell's equations, one can obtain wave equations for the components of the electric and magnetic fields. In the domain of a sinusoidally varying field, this leads to a relationship between the propagation constant of an EM wave in a material and its material functions listed above. This relationship is given as

$$\varepsilon\,(\omega) = \varepsilon_{\text{core}}\,(\omega) + \mathrm{i}\,\sigma/\omega. \tag{1}$$

Let us assume that the only conduction mechanism that we consider is the free carrier motion mechanism. The imaginary part of the dielectric function is then related to this mechanism. Using Drude's theory adapted for semiconductors [4], we derive the complex dielectric function and its components, highlighting the key factors affecting the plasma resonance. The electrical conductivity vs frequency $\sigma(\omega)$ is expressed as

$$\sigma = \frac{n\,e^2\,\tau}{m\,(1-\mathrm{i}\,\omega\tau)}, \tag{2}$$

where e denotes the elementary charge, n is the concentration of free carriers, τ — the momentum relaxation time (representing the collision probability), and m — the effective mass of carriers. This formula can be also derived from the Boltzmann equation. After substituting the conductivity formula into the formula describing the complex dielectric function, we obtain

$$\varepsilon = \varepsilon_{\text{core}} + \frac{\mathrm{i}}{\omega}\,\frac{n\,e^2\,\tau}{m\,(1-\mathrm{i}\,\omega\tau)}. \tag{3}$$

A simple transformation (using the complex conjugate) allows us to extract the real ε_1 and imaginary part ε_2 parts of the function. Therefore,

$$\varepsilon_1\,(\omega) = \varepsilon_{\text{core}} - \frac{n\,e^2\,\tau^2}{m\,(1+\omega^2\,\tau^2)} \tag{4}$$

$$\varepsilon_2\,(\omega) = \frac{1}{\omega}\frac{n\,e^2\,\tau}{m\,(1+\omega^2\,\tau^2)}. \tag{5}$$

Now, we calculate the plasma resonance frequency $\hat{\omega}_p$, which accounts for the influence of free carrier losses on the resonance condition. The plasmon resonance frequency without the caret ω_p in this convention will mean that the influence of losses was neglected. Therefore, by setting the real part of the dielectric function to zero

$$\varepsilon_1\,(\hat{\omega}_p) = 0 = \varepsilon_{\text{core}} - \frac{n\,e^2\tau^2}{m\,\left(1+\hat{\omega}_p^2\,\tau^2\right)}, \tag{6}$$

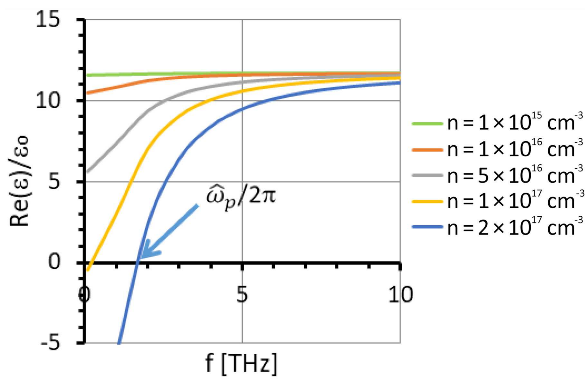

Fig. 1. Real part of the dielectric function (normalized to the permittivity of vacuum) vs frequency for moderately phosphorus-doped silicon at 300 K ($\tau = 0.1$ ps). For all concentrations below ca. 1×10^{17} cm^{-3}, Re(ε) is positive.

one gets

$$\hat{\omega}_p^2 = \frac{n\,e^2}{m\,\varepsilon_{\text{core}}} - \frac{1}{\tau^2} = \omega_p^2 - \frac{1}{\tau^2}. \tag{7}$$

Thus, the number of free carriers required to form a plasma is determined by the condition

$$n > \frac{m\,\varepsilon_{\text{core}}}{e^2\,\tau^2}; \tag{8}$$

otherwise $\hat{\omega}_p^2$ gets negative. Below this threshold concentration, plasmonic effects cannot exist due to the insufficient number of free carriers. Moreover, the conditions for the existence of a surface plasmon in the form of a propagating longitudinal wave are even more stringent than those discussed above, i.e., they would require an even higher concentration of free carriers [5]. For carrier densities lower than those defined by (8), the real part of the dielectric function of the semiconductor never becomes negative (see Fig. 1), i.e., there are not enough free electrons to balance the core contribution to polarization. As it has been shown, free electron losses affecting the plasma resonance frequency have important consequences for the description of THz detection using any plasmon model. Moreover, hole plasmons have never been experimentally detected, which further challenges the model of plasmonic detection in the context of p-type FETs.

Experimental values of the complex dielectric function of semiconductors at terahertz frequencies are rarely found in the literature. They usually refer to the measurement of the complex conductivity of the material (uniquely related to the complex dielectric function) using time-domain spectroscopy (TDS) and most often concern silicon, e.g., [6]. Such measurements are usually performed to confirm the applicability of various versions of the Drude model extended to semiconductors in the THz domain. The results usually concern only a few values of carrier concentration and show an exceptional agreement of this model (even in its simplest versions) for concentrations below the degeneracy threshold of the semiconductor. This is confirmed by the advanced computational modeling of silicon properties in the THz domain presented in [7]. Those TDS experimental data, also obtained by our research group [8], convince us that the use of the Drude model in this work is justified.

It should be noted that in semiconductor electronic devices (like diodes or transistors) the number of free carriers depends not only on the number of introduced dopants but also on the electrode potentials influencing the spatial distribution of carriers. Consider, for example, a typical silicon n-type FET or GaAs/AlGaAs HEMT at room temperature. Both of them detect THz very efficiently if their gate is biased close to the threshold voltage [8], while the electron concentration in their channels in this range is many orders of magnitude smaller than required for plasmon formation. Despite the reduced carrier concentration in this range, THz detection is very effective. This contradicts the use of the plasmonic model. To alleviate the limitations of the plasmon theory, it is proposed to focus on detection models using thermoelectric effects, which do not explicitly take into account the frequency dependence of the detected radiation and may be used for both n- and p-type devices (see, e.g., [9]). Graphene researchers often emphasize the important role of the thermoelectric mechanism (e.g., [10]) in THz detection. The need to take into account the thermoelectric effect in the context of terahertz radiation detection using FETs has already been pointed out in the literature, e.g., in [11, 12]. It should also be mentioned that the discussed plasmon model does not deal with the problem of plasmon generation itself, which is associated with the fulfillment of several difficult conditions described in [5].

3. Conclusions

This paper demonstrates that the widely used formula for plasma resonance often neglects the energy losses associated with carrier motion, leading to erroneous conclusions about plasma formation in semiconductors. Correctly accounting for the carrier relaxation time is essential for the consideration of plasmonic effects, particularly in the context of THz detection near the threshold voltage of FETs. Moreover, the lack of experimentally detected hole plasmons further undermines the credibility of the current plasmon model in the context necessary to understand THz detection by p-channel FETs. Thermoelectric models offer a promising alternative for n- and p-channel transistors, helping to explain the observed photoresponse behaviors. The use of appropriate theory is important in the context of planning the use of THz bands for effective applications related to the implementation of 6G networks. Proper modeling can set a new standard for THz device designers and provide a basis for future advances in physics of detectors operating at frequencies not yet used in mobile telecommunications.

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