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THz Time Domain Spectroscopy of Thin Gold Layers on GaAs

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Thin layers of Au with the thickness of several nanometers were prepared on a semi-insulating GaAs substrate. The layers' thickness was determined by ellipsometry. THz time-domain spectroscopy was applied to determine a complex index of refraction of thin Au layers. The obtained results allow for a more precise modeling of the performance of semiconductor devices at THz frequencies.

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1. Introduction

Semiconductor micro- and nanostructures are very promising candidates for detectors and emitters in THz range of the electromagnetic spectrum [1]. The basic underlying mechanism is a coupling of electromagnetic waves to oscillations of the electron plasma in the semiconductor. As an example, it was proved that field-effect transistors (FETs) can be used as THz detectors at room as well as cryogenic temperatures. Such a coupling of photons to plasmons is usually achieved with a planar metallic antenna connected to the source and gate. In this context, a question arises about THz properties of thin metallic layers deposited on a semiconductor surface which form antenna pads.

Numerical modeling appears to be an indispensable tool to understand THz properties of a FET. THz properties of materials used to fabricate a FET are the input data for computer simulations. On the micro- and submicrometer level, properties of a semiconductor structure or a metallic layer depend on the technology. For this reason, one should determine properties of layers obtained within a technology that will subsequently be used to produce a FET.

We addressed the problem of THz properties of thin Au layers deposited on a GaAs. Such layers form gates semitransparent at THz frequency and antenna metallization pads. The final goal of the investigation is to determine a complex index of refraction of Au deposited on a GaAs substrate in the THz range. The experimental tool was a time-domain spectroscopy based on a fs-laser pulsed system.

2. Experiment

A series of Au layers was prepared on a (100) surface of an epiready semi-insulating GaAs of 320 μm thickness by a dc magnetron sputtering using a Leybold L400cp system. The deposition process was performed in Ar^+ plasma at working pressure 3×10^{-3} mbar, a gas flow of $Ar^+ = 100$ sccm and the power of 300 W. The thickness of the Au layers was measured by ellipsometry and was equal to 8.7 nm and 18.6 nm. Such a small thickness was used to enable transmission experiments in the THz range. We have verified that the layers thicker than 50 nm are opaque to THz radiation.

The experiment was performed with so-called THz time domain spectroscopy method (THz TDS). A photoconductive THz emitter excited by a 150 fs duration, 76 MHz repetition rate, and 810 nm central wavelength pulses from a mode-locked Ti:sapphire laser was used as a THz source in the range 0.1–1.5 THz. THz radiation was transmitted through the sample placed in an optical cryostat and collected by an ultrafast photodetector with a dipole antenna and a substrate lens made from a high resistivity silicon. The detector was manufactured from a low-temperature GaAs grown by the molecular beam epitaxy at about 250 °C substrate temperature. It showed an electron trapping time of about 200 fs, thus the signal at the photodetector appears when the carriers are present shortly after the excitation by fs pulse. The fs photoexcited carriers are driven by THz electric field interacting with dipole antenna, they reach electric contacts and finally are detected by lock-in amplifier.

3. Results

In a THz TDS experiment, one records a voltage on the photodetector as a function of a delay between the THz pulse and the reference ultrashort fs (duration less than 40 fs) pulse from a Ti:sapphire laser. The spectrum consists of several peaks (with positive or negative sign) with the amplitude decreasing with the increase of the delay time, which originate from multiple reflections of THz radiation inside the sample (Fig. 1). The time interval between successive peaks, as well as their phase depends on the thickness of the sample and its complex index of refraction. The strongest signal is obtained when the light transmitted through the sample without any internal reflection arrives at the photodetector at the same time as a reference fs pulse. Positive and negative sign of voltage means that the phase of THz electric field recorded by the dipole antenna varies with delay time.

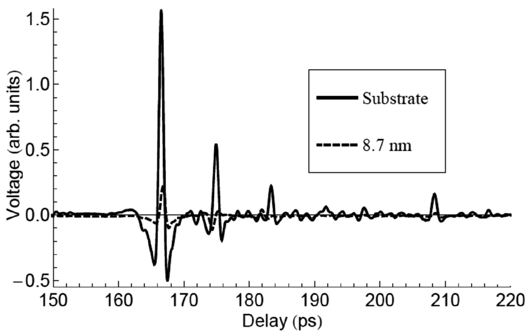

Fig. 1. Results of a THz TDS experiment on GaAs sample. Voltage signal of transmission through the substrate is compared with voltage signal of transmission through Au layers of 8.7 nm thick.

4. Data analysis

In order to obtain a spectrum in the energy domain, rather than in the time domain, one has to Fourier transform time-dependent results (Fig. 2). In our case, we have got spectra dominated by a Fabry–Perot etalon pattern resulting from interferences in the GaAs substrate. The spectrum consists of several peaks with the amplitude decreasing with the increase of the frequency (Fig. 2). A reference spectrum was obtained by measurements of the transmission without the sample. The signal processed by a numerical analysis was a spectrum of transmission through a sample ("sample spectrum") divided by the reference spectrum.

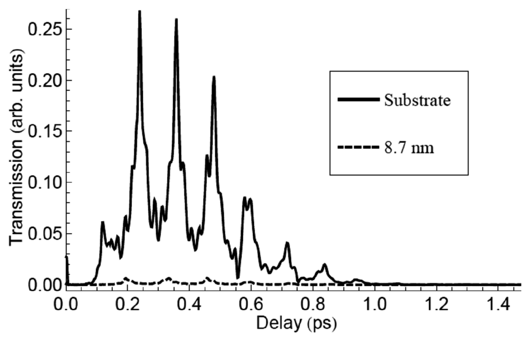

Fig. 2. Results of a Fourier transformation of a time-domain spectrum. The transmission from the substrate is compared with the transmission of Au layer of 8.7 nm.

The transmission data were analyzed with a standard transfer matrix method of the form of

$$M_m = \frac{1}{t_{m-1,m}} \begin{bmatrix} 1 & r_{m-1,m} \\ r_{m-1,m} & 1 \end{bmatrix} \begin{bmatrix} \mathrm{e}^{-\mathrm{i}\delta_m} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}\delta_m} \end{bmatrix},$$

where M_m is a transfer matrix through the layer m by light passing from layer denoted as $m-1$; the symbols $t_{m-1,m}$ and $r_{m-1,m}$ represent, respectively, amplitude transmission and reflection coefficients between the neighboring layers. Since we used a configuration of a normal incidence, TM and TE transmission and reflection coefficients are the same. The term $\mathrm{e}^{-\mathrm{i}\delta_m}$ represents propagation of the light in the medium m. Relative amplitudes of the transmitted and reflected waves at an interface between two media are given by Fresnel's coefficients depending on refractive indexes n_{m-1} and n_m. The term $\delta_m = n_m d_m \frac{\omega}{c}$ represents an optical path length, where c is the light velocity, ω is the frequency and d_m is the thickness of the layer.

In the case of dissipative media — like metallic layers — refractive indexes are complex. By modeling the dependence of n_m on the frequency ω one can obtain the transmission coefficient $T(\omega)$ of the measured multilayered system.

For a GaAs substrate we took a real value of $n_{\mathrm{GaAs}} = 3.6$. For an Au layer we took a dependence given by the Drude model of dielectric function $\varepsilon(\omega)$ of damped plasma frequency [2–4]:

$$n^2(\omega) = \varepsilon(\omega) = 1 - \frac{\omega_{\mathrm{p}}^2}{\omega^2 + \mathrm{i}\omega\omega_\tau},$$

where ω_{p} is the plasma frequency of gold and ω_τ is its damping frequency. It is not possible to obtain ω_{p} and ω_τ independently since both are related to the so-called optical conductivity $\sigma_{\mathrm{opt}} = \varepsilon_0 \frac{\omega_{\mathrm{p}}^2}{\omega_\tau}$. Therefore we assumed bulk value of $\omega_{\mathrm{p}} = 2186$ THz, which was used for photons energies 10–660 THz [3–5] and we fitted only σ_{opt}.

The measured intensity $I^{\mathrm{exp}}_{\mathrm{GaAs/Au}}(\omega)$ of the GaAs/Au spectrum in Fig. 2 consists of the transmission coefficient $T_{\mathrm{GaAs/Au}}(\omega)$ and unknown envelope of the intensity of the THz source $I_0^{\mathrm{exp}}(\omega)$:

$$I^{\mathrm{exp}}_{\mathrm{GaAs/Au}}(\omega) = T_{\mathrm{GaAs/Au}}(\omega) I_0^{\mathrm{exp}}(\omega).$$

In order to obtain $I_0^{\mathrm{exp}}(\omega)$ we also measured the intensity of the THz radiation through the GaAs substrate $I^{\mathrm{exp}}_{\mathrm{GaAs}}(\omega)$ and modeled transmission $T_{\mathrm{GaAs}}(\omega)$. Finally, we fitted parameters of gold in the spectrum $I^{\mathrm{exp}}_{\mathrm{GaAs/Au}}(\omega)$ divided by $I^{\mathrm{exp}}_{\mathrm{GaAs}}(\omega)$:

$$\frac{I^{\mathrm{exp}}_{\mathrm{GaAs/Au}}(\omega)}{I^{\mathrm{exp}}_{\mathrm{GaAs}}(\omega)} = \frac{T_{\mathrm{GaAs/Au}}(\omega)}{T_{\mathrm{GaAs}}(\omega)}. \tag{1}$$

We found that it was difficult to obtain good results using the spectra $I^{\mathrm{exp}}_{\mathrm{GaAs}}(\omega)$ measured on the same substrate thickness as in GaAs/Au sample. The reason is that $T_{\mathrm{GaAs}}(\omega)$ is a transmission of a Fabry–Perot etalon — which is just periodic function of optical path length δ_{GaAs} and thus of ω. Therefore, if periods of $T_{\mathrm{GaAs/Au}}(\omega)$ and $T_{\mathrm{GaAs}}(\omega)$ are too close one to the other, then an experimental uncertainty of the measured values $I^{\mathrm{exp}}_{\mathrm{GaAs/Au}}(\omega)$ and $I^{\mathrm{exp}}_{\mathrm{GaAs}}(\omega)$ strongly modifies quotient results. Such uncertainty can be for instant created by a small difference between the angle of incidence of the THz radiation passing through GaAs/Au and GaAs and therefore slightly different optical path length in GaAs substrate. Intentionally, the light was passing through the sample at the normal incidence, however it was not controlled with a precision better than 10 degrees.

The best solution was to measure $I^{\exp}_{\mathrm{GaAs}}(\omega)$ on a substrate of an essentially different thickness $d_{\mathrm{GaAs}} = 350\ \mu\mathrm{m}$ than the thickness of the GaAs/Au sample (320 μm). Thus small deviation from normal angle of incidence of THz radiation was corrected in calculations by the small deviation of the nominal thickness of GaAs substrate (below 2%), which — contrary to the situation described before — did not change significantly the shape of the $I^{\exp}_{\mathrm{GaAs/Au}}(\omega)$ and $I^{\exp}_{\mathrm{GaAs}}(\omega)$ ratio.

The results of the experimental ratio $I^{\exp}_{\mathrm{GaAs/Au}}(\omega)/I^{\exp}_{\mathrm{GaAs}}(\omega)$ and calculated $T_{\mathrm{GaAs/Au}}(\omega)/T_{\mathrm{GaAs}}(\omega)$ are presented in Fig. 3.

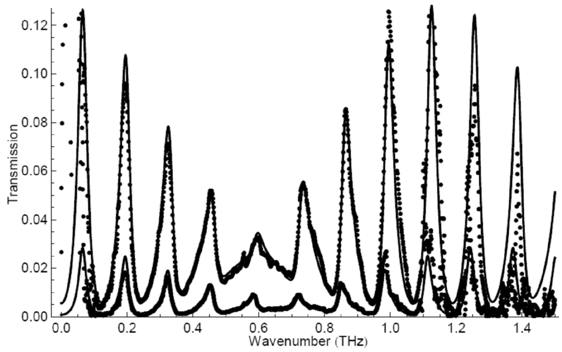

Fig. 3. The results of the fit (solid lines) of Eq. (1) to the experimental data — upper points: spectrum $I^{\exp}_{\mathrm{GaAs/Au}}(\omega)/I^{\exp}_{\mathrm{GaAs}}(\omega)$ of GaAs/Au 8.7 nm, lower points — spectrum of GaAs/Au 18.6 nm.

We varied the thickness of GaAs substrate d_{GaAs} (nominally 320 μm), and the refractive index of Au layer (n_{Au}). We assumed values of d_{Au} taken from the ellipsometry experiments. Fitting the amplitude of the etalon spectrum and the distance between maxima one can get the full information about the thickness of the sample and the complex indexes of refraction of constituent layers. The obtained parameters for Au are presented in Table (frequency ν is given in THz, $\omega = 2\pi\nu$).

TABLE

Summary of the fitting procedure.

d_{Au} [nm] (ellipsometry)	ν_{p} Au [THz]	ν_{τ} Au [THz]	σ_{opt} [$(\Omega\ \mathrm{cm})^{-1}$]	n_{Au} [1 THz]
18.6	2186	34.5	770 000	$259.3 + 266.9\mathrm{i}$
8.7	2186	38.2	700 000	$246.8 + 253.3\mathrm{i}$

The bulk value of the optical conductivity for the wave number range of 10–10^5 cm^{-1} is about 411000–450000 $(\Omega\ \mathrm{cm})^{-1}$ ([4] and references therein).

5. Conclusions

The results of transmission of THz radiation over Au layers were analyzed with a transfer matrix method which allowed for determination of the refractive index of Au. From these investigations the optical parameters of Au thin layers were determined. The results allow for a better modeling of devices and understanding their THz response.

Acknowledgments

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