OPTICAL PROPERTIES OF FILMS

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OPTICAL PROPERTIES OF FILMS ON SEMICONDUCTOR SUBSTRATES

1. In recent years the range of scientific problems and technical applications associated with films deposited on semiconductor substrates has been rapidly expanding. These include problems of growing films of perfect structure (^{1}), creating thin-film triodes with an insulated gate and other active devices of dielectric electronics (^{2}), developing devices based on the film–substrate heterojunction (^{3}), and depositing passivating coatings on semiconductors (^{4}). Up to the present time, this rapidly developing area of the physics and technology of thin films has been practically devoid of optical methods of investigation—one of the most effective and delicate tools for studying both the macro- and microcharacteristics of solids. Owing to the opacity of the semiconductor substrate, only the reflection method is used here, which substantially narrows the information possibilities of optical investigations.

In the present work we show the possibility of studying films on opaque semiconductor substrates by means of measurements of light transmission. To indicate the light passing through the film, it is proposed to use the physical properties of the substrate that are sensitive to the action of the light flux (photoconductivity, photoelectromagnetic effect, etc.). With such an approach, the strong absorption of light in the substrate material ceases to be an obstacle and becomes a means for studying the optical properties of films.

The possibility of direct measurement of the transmission of a film on an opaque semiconductor substrate seems to us timely and important, since the optical properties of films depend substantially on the conditions of their preparation (^{5}). Therefore, without measurements of the properties of a film located directly on a semiconductor substrate, information on the optical characteristics of these films cannot be considered at all reliable.

2. The optical properties of a film are determined by the spectra of the absorption coefficient $k(\lambda)$ and the refractive index $n(\lambda)$. To determine them in the general case it is necessary to measure the transmission spectra $T(\lambda)$ and reflection spectra $R(\lambda)$ of the film. In the known expressions (^{6}) for R and T of a film

Fig. 1. Gallium arsenide film on a germanium substrate. 1 —illumination of the free surface of germanium, 2 —illumination through the film

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located on an absorbing substrate, in the general case the optical characteristics n and k of both the film and the substrate enter. For semiconductor substrates, for which the absorption index $\chi = k(\lambda)/4\pi \ll 1$, the influence of absorption in the substrate on $R(\lambda)$ and $T(\lambda)$ may be neglected.

For films, in contrast to massive samples, the optical constants can be determined from measurements of $T(\lambda)$ alone, if the measurements are carried out in the region of strong and in the region of weak absorption. Indeed, in this case the refractive index is found directly from the interference maxima and minima in the transparency region of the film. In addition, the interference pattern determines the layer thickness d, and, consequently, the need for an independent measurement of d, usually connected with destruction of the sample, is eliminated.

Knowledge of $n(\lambda)$ for the film in the transparency region makes it possible in most cases to dispense with measurements of $R(\lambda)$ also in the region of strong absorption of the film. Indeed, usually n varies only weakly with λ, and therefore it can be extrapolated into the region of strong absorption, all the more so since there $k(\lambda)$, determined from $T(\lambda)$, depends only weakly on n. This extrapolation can be carried out with still greater confidence if $n(\lambda)$ in the region of weak absorption agrees with known literature data for single crystals or films of the given material.

3. To register the light transmitted through the film, we used the photoconductivity of the substrate in the region of intrinsic absorption. For this it is necessary that the band gap of the substrate material be smaller than the band gap of the film, which is especially important in studying the structure of the edge of intrinsic absorption.

Fig. 1. Gallium arsenide film on a germanium substrate. 1 —illumination of the free surface of germanium, 2 —illumination through the film

Gallium arsenide films on germanium substrates were studied; they were obtained by rapid evaporation from a piece of material in a vacuum of 10^{-6} torr. Films of two types were obtained: textured (at a substrate temperature $\simeq 500^\circ$) and amorphous (when deposited on a cold substrate).

The geometry of the samples is shown in Fig. 1.

Measurements were carried out by the method of low-frequency (400 Hz) modulation of the light flux. The signal on the substrate was registered by a selective microvoltmeter V6-6. For monochromatization of the light a prism instrument ISP-51 was used.

Determination of the transmission of the film $T(\lambda)$ was based on comparison of the photoconductivity signals under illumination of the free surface of the substrate (1 in Fig. 1)

$$\Delta\sigma_1 = q\mu\beta\tau(1 - R_1)I_0 \tag{1}$$

and under illumination of the substrate through the film (2 in Fig. 1)

$$\Delta\sigma_2 = q\mu\beta\tau T I_0. \tag{2}$$

From (1) and (2) we find

$$T = \frac{\Delta\sigma_2}{\Delta\sigma_1}(1 - R_1). \tag{3}$$

The experimental curve $\Delta\sigma_2/\Delta\sigma_1$, constructed from the results of measurements of $\Delta\sigma_1$ and $\Delta\sigma_2$ for a textured GaAs film on n-type Ge ($\rho = 32\ \Omega \cdot \mathrm{cm}$, germanium reflection coefficient $R_1 = 0.36$), is given in Fig. 2a (curve 1′).

Using expression (6)

$$\frac{T_{\max}}{T_{\min}} = \left(\frac{1 + \sqrt{R_2 R_3}}{1 - \sqrt{R_2 R_3}}\right)^2 = \left[\frac{(1 + n_1)n_2}{n_1 + n_2^2}\right]^2, \qquad 2n_2 d = m\frac{\lambda}{2}, \tag{4}$$

where n_1, n_2 are the refractive indices of the substrate and the film (for germanium $n_1 = 4$), we determine the film thickness d and the spectrum of its refractive index $n_2(\lambda)$ from the magnitude and position of the interference extrema on the curve $\frac{\Delta\sigma_2}{\Delta\sigma_1}(\lambda)$. Here R_2, R_3 are the reflection coefficients at the air-film and film-substrate boundaries, related to the refractive indices by the Fresnel formulas. For the GaAs films we studied, $d \sim 0.5 \div 1\ \mu$. The values of the refractive index calculated from curve 1 of Fig. 2a···

the refractive index of the textured film in the region $1000 \div 1300$ mμ practically does not depend on λ and is equal to $\simeq 3.6$, which lies within the range of values reported in the literature for gallium arsenide single crystals (7).

On the curves $\frac{\Delta\sigma_2}{\Delta\sigma_1}(\lambda)$ for amorphous films, interference extrema are absent (Fig. 2b). It is possible that the refractive index of amorphous gallium arsenide films differs from the refractive index of the single crystal and is close to the refractive index of germanium. Therefore, in the case of amorphous films the thickness was determined from control films on glass using an MII-4 microinterferometer.

Fig. 2. **a** –spectra of the relative photoconductivity of textured GaAs films on a germanium substrate. **1** –n-type substrate; **2** –p-type substrate. **b** –

Fig. 2

Figure 2: Fig. 2

spectrum of the relative photoconductivity of an amorphous GaAs film on n-type germanium

Calculation of $k(\lambda)$ from the measured $T(\lambda)$ is carried out by the well-known formula (^{8})

$$T = \frac{16 n_1 n_2^2}{(1+n_2)^2(n_1+n_2)^2 e^{kd} + (1-n_2)^2(n_2-n_1)^2 e^{-kd} + 2(1-n_2^2)(n_2^2-n_1^2)\cos\frac{4\pi n_2}{\lambda}d}. \tag{5}$$

In the absence of interference, determination of $k(\lambda)$ from $T(\lambda)$ is simplified ($n_1 = n_2 = n$):

$$k = \frac{1}{d}\ln\frac{4n}{(1+n)^2 T}. \tag{6}$$

The spectra $k(\lambda)$ for textured and amorphous GaAs films are given in Fig. 3. For comparison, the curves for amorphous and textured films on a transparent substrate (^{9}), as well as data for gallium arsenide single crystals (^{10}), are also shown there. As can be seen from the figure, $k(\lambda)$ for amorphous films on germanium and on glass are close to one another, while for textured films on a germanium substrate, in the region of small k, the curve is closer to that for the single crystal than in the case of films on glass.

4. Up to now the entire discussion has been carried out as if the film on a semiconductor substrate plays the role only of an optical filter, without changing the physical properties of the substrate. In this case, in the spectral region of total transmission, where interference is observed at λ corresponding to the minimum of $T(\lambda)$*, the ratio of the photoconductivities under the GaAs film and on the free surface of germanium should be equal to unity

$$(\Delta\sigma_2/\Delta\sigma_1)_{\min} = T_{\min}/(1-R_1) = 1. \tag{7}$$

* In the case where $n_2 > n_1$, this will be valid for the maximum of $T(\lambda)$.

However, deposition of a film can cause a number of physical effects—changes in the spectrum of surface levels and in the effective lifetime in the substrate, the appearance of a heterojunction at the film-substrate contact, etc. In this case, the photoconductivity of the substrate under the film in the interference region will differ from the photoconductivity produced when its open surface is

Figure 3

Figure 3: Figure 3

illuminated. The criterion for the occurrence of such effects is the deviation of the ratio $\Delta\sigma_2/\Delta\sigma_1$ from unity. Such results were obtained by us when using p-type germanium as the substrate ($\rho = 10\ \Omega \cdot \text{cm}$), where for different specimens $(\Delta\sigma_2/\Delta\sigma_1)_{\min} = 3 \div 6$ (curve 2 in Fig. 2a).

All photoelectric effects caused by the presence of a film on a semiconductor substrate can be formally taken into account by introducing into formula (2) a certain effective lifetime τ^*, different from τ near the free surface of the substrate. In this case

$$\frac{\Delta\sigma_2}{\Delta\sigma_1} = \frac{T}{(1 - R_1)}\,\frac{\tau^*}{\tau}. \tag{8}$$

Fig. 3. Spectra of the absorption coefficients of gallium arsenide. 1—textured film on a germanium substrate; 2—amorphous film on a germanium substrate; 3—textured film on glass (^{9}); 4—amorphous film on glass (^{9}); 5—single crystal (^{10})

If the presence of a film on the surface of a semiconductor in fact changes only the lifetime in the semiconductor, then $T(\lambda)$ can be found by the former method, by renormalizing $(\Delta\sigma_2/\Delta\sigma_1)_{\min}$ in the transparency region of the film to unity. In this case $(\Delta\sigma_2/\Delta\sigma_1)_{\min}$ is equal to the ratio of the effective lifetimes τ^*/τ. If, however, the photoconductivity of the substrate is distorted by the overflow of photocarriers through the heterojunction, then the determination of $T(\lambda)$ becomes a more complicated problem, which will be considered separately. We note only that the experimenter still has the possibility of controlling the process of photocarrier overflow by applying an electric voltage to the film-substrate system in a direction perpendicular to the photoconductivity current, or by additional illumination.

It may be thought that this additional experimental degree of freedom will make it possible to broaden the described method for determining optical constants, and also to use it for investigating the properties of heterojunctions.

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Note: Figure translations are in progress. See original paper for figures.