Semiconductor Physics, Quantum Electronics & Optoelectronics. 2002. V. 5, N 3. P. 300-302.

PACS: 78.20.-e

Influence of surface dimensional effects and interband transitions on absorption of light in aluminium

L.Yu. Melnichenko, B.B. Tytarchuk, I.A. Shaykevich
Department of Optics, Physics Faculty, Taras Shevchenko Kyiv National University, 6 prosp. Glushkova, 03127 Kyiv, Ukraine
E-mail:shaykevi@phys.univ.kiev.ua

Abstract. Optical conductivity of aluminium with of large roughness surface were measured by a spectroellipsometric method in visible, near infrared and near ultra-violet region of the spectrum. Aluminium foil was used as a sample. Comparison of the received results for rough and smooth surfaces of aluminium were performed. It is revealed that the absorption peak on the spectral curve of optical conductivity with a maximum near $\lambda = 0.8$ μm for a rough surface of aluminium is considerably wider than for smooth surface, although it has less intensity. An additional maxima near $\lambda = 0.35$ μm and $\lambda = 0.97$ μm take place for rough surface spectrum. The broadening and additional maxima are accounted for the basis of consideration of model of a surface layer of rough surface of aluminium, as heterogeneous thin layer, in which plasma resonance, resonance of optical conductivity, and also the interaction of these resonances with interband transitions occur.

Keywords: resonance of optical conductivity, plasma resonance, large rough surface, absorption peak

Paper received 12.06.02; accepted for publication 10.12.02.

1. Introduction

Rough surface of metal can be interpreted by a heterogeneous plane-parallel surface layer, that consists of metal particles and air intervals between them. Consequently, there can be electron plasma fluctuations with the certain plasma frequency [1], which result in the appearance of a resonant maximum on the spectral curve of optical conductivity (absorption). In such systems, there can be one more type of resonances, namely, the resonance of optical conductivity (ROC), which is also observed as a maximum on the spectral curve of optical conductivity [2]. Eventually, in metals there are electronic interbands transitions, which also give the certain maximum on the spectral curve of optical conductivity. As shown in [2], all these types of resonances can cooperate with each other, which results in occurrence of additional maxima. We have described also the investigation of these features for a rough surface of aluminium.

2. Experiment

Aluminium foil was chosen to represent a rough sample of Al. The profile of its surface was registered using Dektak 3030. Then the profile curve of the surface was processed by computer program and the average arithmetic deviation of the surface profile from a straight line R_a was determined. It appeared to be 4.1 μm for the researched sample. The processing of the area under the profile curve of a surface gives an opportunity to determine also the so-called "factor of filling" in a heterogeneous surface layer q, i.e. volume share of metal in an overall mixture air - metal. This value appeared to be equal 0.4. Then the spectroellipsometric measurements of the sample using a spectroellipsometer by the Beatty method [3] was carried out. We proposed modernization of the Beatty method for metal and semi-conductor rough surfaces [4] and used it. The ellipsometric parameters for different light wavelength for near ultra-violet, visible and near infrared regions of the spectrum were measured. Then the optical constants, namely, index of refraction *n* and index of absorption æ were calculated. The optical conductivity σ that actually characterizes absorption of light in the object was calculated using obtained optical constants.

3. Results and discussion

Optical constants of aluminium were investigated in many works in a wide range of the spectrum [3]. It is known that in near infrared range aluminium has the absorption peak at the wavelength $\lambda = 0.8$ μm, which is caused by two types of interband transitions in *K* and *W* points of the

Brillouin zone. In experiments described in the work [5] using polariton researches, it was possible to experimentally observe these transitions as two maxima on the spectral curve of optical conductivity for a smooth surface of aluminium for the first time. The peak at $\lambda = 0.8$ μm was related to transitions in K point of the Brillouin zone.

The results received in the present work for a large rough surface of aluminium are shown in Fig. 1. The spectral curve 1 corresponds to our measurements, and the spectral curve 2 corresponds to a smooth surface of aluminium. Results for curve 2 is taken from the work [6]. The comparison of both curves shows that the rough surface of aluminium has the absorption peak with a maximum near $\lambda = 0.8$ μm considerably in its intensity than smooth surface, wider in its halfwidth and, eventually, contains two additional small maxima at $\lambda \approx 0.35$ μm and $\lambda \approx 0.97$ μm.

It is known [2] that there are two types of resonances in heterogeneous metallic layers, namely: ROC and plasma resonance (PR).

The ROC frequency conforms to [2]:

$$\omega_{ROC} = \left[\frac{1}{3}\omega_p^2(1-q)\right]^{1/2} \tag{1}$$

where q is the filling factor, ω_p is a plasma frequency,

$$\omega_p = \left(\frac{4\pi N e^2}{m}\right)^{1/2}, \tag{2}$$

where N is a concentration of conductivity electrons; e – electron charge; m – electron mass.

The PR frequency is determined by the formula:

$$\omega_{PR} = \left[\frac{1}{3}\omega_p^2(1+2q)\right]^{1/2} \tag{3}$$

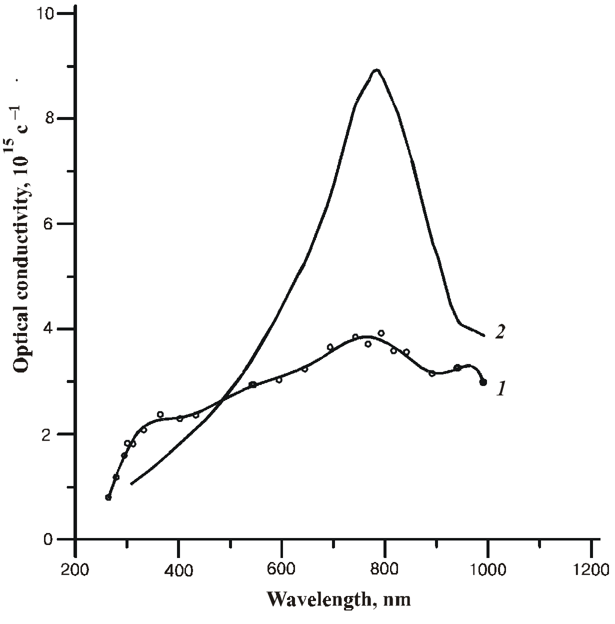

Fig.1. Dependence of the optical conductivity, σ, on the wavelength, λ, for the sample of Al with large rough surface (curve *1*) and with smooth surface (curve *2*).

Designations in (3) are the same as in (1).

Eventually, if in a heterogeneous layer interband transitions are present, owing to interaction of interband transitions with both kinds of resonances that were mentioned above, there are additional resonant maxima to the left and to the right of a peak caused by interband transitions. The relative frequencies of these additional resonances are determined by the ratio [2]:

$$\Omega_{1,2} =$$

$$= \left(\frac{1}{2}\right)^{1/2} \left\{\Omega_0^2 + (1+\varphi) \pm \left[\Omega_0^4 - 2\Omega_0^2(1-\varphi) + (1+\varphi)^2\right]^{1/2}\right\}^{1/2} \tag{4}$$

where $\Omega_0 = \omega_M/\omega_K$; ω_M – circular frequency of interband transition, ω_K – frequencies ROC or PR (formulae (1), (3)) depending on what interaction of a resonance with the interband transition is considered; $\Omega_{1,2} = \omega_{1,2}/\omega_K$; $\omega_{1,2}$ – frequencies additional resonances, φ – average oscillator force of the interband transition.

At $q = 0.4$, as obtained by us above, the circular ROC frequency was calculated by means of the formulae (1) and (2). The concentration of electrons for aluminium N was taken from the work [7]. It was received that $\omega_{\mathrm{ROC}} = 6.46 \cdot 10^{15}$ rad/s, $\lambda_R = 2.9 \cdot 10^{-5}$ cm. Taking into account that the short-wave peak on the spectral curve of optical conductivity (Fig. 1, curve 1) corresponds to $\lambda_1 \approx 0.35$ μm and circular frequency $\omega_1 = 5.38 \cdot 10^{15}$ rad/s, that is ω_{ROC} locations in borders of this short-wave peak, it is possible to reach the following conclusion. The short-wave peak can be related to the resonance of optical conductivity. If we take ROC circular frequency $\omega_{\mathrm{ROC}} = \omega_1$, it is possible to calculate the filling factor using the formulae (1) and (2). It has appeared that $q_1 = 0.58$, which is in comparison with $q = 0.4$ is a little bit higher. Such divergence is possible to explain by assumption that a heterogeneous surface layer in the theories mentioned above is extrapolated by a plane-parallel layer with spherical, or ellipsoidal particles of metal. At the same time, the metal parts in a real surface layer have a more complicated form. If we consider now the long-wave maximum in Fig.1 (curve 1), i.e. $\lambda_2 \approx 0.97$ μm and $\omega_2 = 1.94 \cdot 10^{15}$ rad/s, as a resonant long-wave maximum, which is caused by interaction of ROC with interband transitions. Then using formula (4), one can obtain an average oscillator force of the interband transitions φ in K point of the Brillouin zone. At $\omega_{\mathrm{ROC}} = 6.46 \cdot 10^{15}$ rad/s and $q = 0.4$ it appeared that $\varphi = 0.45$. At $\omega_{\mathrm{ROC}} = \omega_1 = 5.38 \cdot 10^{15}$ rad/s and $q_1 = 0.58$, $\varphi_1 = 0.43$. As seen, the values of average oscillator force are very close in both cases. It is interesting to consider the long-wave maximum in Fig. 1 (curve 1) from the viewpoint of PR and its interaction with interband transitions. Using both values q and q_1, these two values of PR frequency were received by means of the formula (3): $\omega_{\mathrm{PR}} = 1.12 \cdot 10^{16}$ rad/s and $\omega_{\mathrm{PR}1} = 1.23 \cdot 10^{16}$ rad/s. Both frequencies lay in far ultra-violet range of spectrum and they could not be observed by our experimental equipment. If we now consider the long-wave peak in Fig. 1 (curve 1) as a result of interaction of plasma fluctuations with the interband transitions in K point of Brillouin zone, then we received two values of the average oscillator force. These values coincide with the second mark after a point, that is $\varphi = \varphi_1 = 0.48$. As seen, the result received above is very close to the values of ROC interaction with interband transitions in K point. Thereof, it is possible to conclude, that the long-wave resonant peak of ROC and PR interaction with the interband transitions in K point of the Brillouin zone in the case, researched by us, practically coincides with that of the rough aluminium surface. As to short-wave peak (mark (+) in the formula (4)), as it is shown by calculations, they lay in a far ultra-violet range of the spectrum and they could not be investigated in our experiment.

Basing on the results of all calculations it is possible to consider that the average oscillator force for interband transitions in K point of the Brillouin zone of aluminium for a sample, researched by us, appears to be $\varphi = 0.45$. It is necessary to note that widening the absorption peak for rough surface of aluminium with the maximum $\lambda \approx 0.8$ µm in comparison with smooth surface can be caused not only by ROC and PR resonances and their interaction with interband transitions mentioned above, but also by reduction of electron lifetime in the excited state, which is in an inverse proportion to the width of absorption peak.

4. Conclusions

It is confirmed experimentally that absorption peak for a rough surface of aluminium caused by interband transitions in W and K points of the Brillouin zone is considerably wider than similar peak for a smooth surface lying in the near infrared range of the spectrum. Its broadening is explained by occurrence of ROC and PR resonances on a rough surface of aluminium, which can be considered as a heterogeneous thin layer, and also by interaction of ROC and PR with interbaned transitions in K point. The average oscillator force of interband transition for aluminium in K point of the Brillouin zone is calculated. Reduction of the electron lifetime in the excited state for the rough surface can also influence on resulting broadening of the investigated absorption peak.

References

1. E.F. Venger, A.V.Goncharenko, M.L. Dmytruk. *Optics of small particles and dispersed media*, Kiev, 1999.
2. Yu.I.Petrov, *Physics of small particles*, Nauka, Moscow (1982).
3. M.M.Noskov, *Optical and magnetooptical properties of metals*. Ural scientific center, Academy of sciences of the USSR, Sverdlovsk (1983) (in Russian).
4. L.Yu. Melnichenko, B.B. Tytarchuk, I.A. Shaykevich, Spectroellipsometrical measurement of large roughness surface in Abstracts, XV International School-Seminar “Spectroscopy of molecules and crystals”, Kyiv, p.24 (2001).
5. V.A. Bolottsev, L.Yu. Melnichenko, V.Yu. Pas’ko, I.A. Shaikevich, Optical properties of copper and aluminium studied with consideration for a surface layer using ordinary and polariton spectroellipsometry // *Functional Materials*, **2** (2), pp.287-290 (1995).
6. Weaver J.H., Kafka C., Lynch D.W., Koch E.E., *Optical properties of metals*, v.I,II, Internal report D.E.S.I.F.41, - Hasylab. 81/01, 172 p., -25p. (1981).
7. G.P.Motulevich , Optical properties of non-transition metals // *Proc. of the P.N.Lebedev Physical Institute*, Academy of sciences of the USSR, **55**, pp. 7-150, (1971) (in Russian).