Optical Constants of Silicon in the Extreme Ultraviolet Region

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(Received February 6, 1962)

The optical constants n and k of a single crystal of silicon were determined by measurements of the reflectance at two angles of incidence in the region 10 to 19.2 eV. Energies of plasma oscillation derived from the optical data agree with the values from the electronic energy loss experiments, being about 17 and 11 eV for the normal (or bulk) plasmon and the tangential (or surface) plasmon, respectively.

THE complex index of refraction $n-ik$ of the single crystal of silicon was determined recently by Philipp and Taft up to 10 eV by applying the Kramers–Kronig relation to normal incidence reflection data.[1] In the measurement described below, it was extended to higher energies up to 19.2 eV using another technique for determination of optical constants.

The specimen used is a disk of 28-mm diam×2 mm of n-type (40 Ω cm) single crystal cut along the (111) plane, polished mechanically, soaked with HF for 90 sec, and then rinsed several times with acetone. Immediately after the wet specimen was mounted in the reflectometer, the chamber was evacuated. The monochromator is a Seya–Namioka type vacuum spectrometer with a 1-m concave grating blazed at 750 Å, supplied by Bausch & Lomb. The source employed is a condensed spark of Weissler's type[2] operated at 7 kV, 10 mA, flowing He at 100 μ Hg as carrier gas, mixed with N_2 at about 10 μ Hg.

Reflection measurements were carried out with a reflectometer assembly attached to the monochromator. The reflectometer chamber can be rotated as a whole about the incident beam axis to 90°, so that the plane of incidence for the surface of the specimen is placed in either vertical or horizontal plane leaving the angle of incidence unchanged. Since it is usual that the incident beams from the monochromator are partially polarized, reflectances measured at these two positions, namely, R_v and R_h, respectively, should be averaged to give the reflectance for the unpolarized incident beam R as

$$R=(R_v+R_h)/2.$$

The optical constants are obtained from a set of two values of reflectance R for incident angles 20° and 70° with the aid of a chart.[3] Further details about the procedures employed in these measurements will be described in another paper.[4]

The results are illustrated in Figs. 1 to 4. The reflectances for incident angles 20° and 70° are shown in Fig. 1, in the range 10.2 to 19.2 eV, together with the estimated uncertainties for repeated measurements, which is usually less than 10% at 20° and 5% at 70°. The optical constants derived from these data using the chart are plotted in Fig. 2, including the results for the region below 10 eV obtained by Philipp and Taft[1].

The spectral region covered by the present experiment is of particular interest because the plasma oscillation of the valence electrons of silicon is believed to take place in this region.[5] According to Marton and Leder,[6] the characteristic energy loss of fast electrons in silicon lies at 16.9 eV, in accordance with the value of the "free electron plasma" energy calculated by assuming that all the valence electrons outside the closed shell contribute to the plasma oscillation.

The energy at which the plasmon can exist will be also determined optically by examining the behavior of the real part of the complex dielectric constant, $\epsilon'=n^2-k^2$. In this connection, the criteria for existence of tangential plasmon recently derived by Kanazawa,[7] were also examined. According to Kanazawa, the tangential (or surface) plasmon will exist when $n^2-k^2+1=0$, or the imaginary part of $1/(\epsilon+1)$, which is equal to the quantity $2nk/[(n^2-k^2+1)^2+4n^2k^2]$, plotted against $\hbar\omega$ has a peak, whereas the normal (or bulk) plasmon can exist when $n^2-k^2=0$, or the imaginary part of the reciprocal dielectric constant, i.e., the quantity $2nk/(n^2+k^2)^2$ as a function of $\hbar\omega$ has a peak.[8]

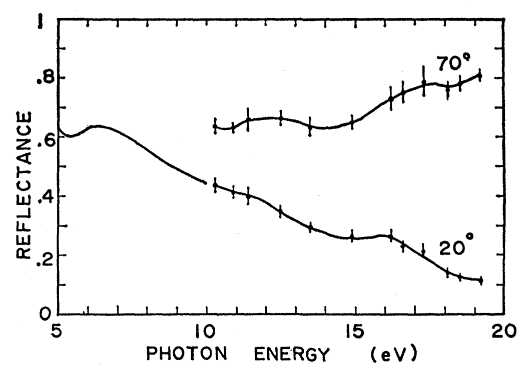

FIG. 1. The spectral dependence of the reflectance of silicon at the angles of incidence 20° and 70°.

[1] H. R. Philipp and E. A. Taft, Phys. Rev. **120**, 37 (1960).
[2] Po Lee and G. L. Weissler, J. Opt. Soc. Am. **42**, 80 (1952).
[3] The method of Tousey-Šimon was improved and a single chart, with which n and k are read directly from a set of observed reflectances, was prepared. See K. Ishiguro, T. Sasaki, and S. Nomura, Sci. Papers Coll. Gen. Educ. Univ. Tokyo **10**, 207 (1960).
[4] A description of the apparatus and techniques will be submitted to the Japanese Journal of Applied Physics.
[5] D. Pines, *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press Inc., New York, 1955), Vol. 1, p. 367.
[6] L. Marton and L. B. Leder, Phys. Rev. **94**, 203 (1954).
[7] H. Kanazawa, Progr. Theoret. Phys. (Kyoto) **26**, 851 (1961).
[8] H. Fröhlich and H. Pelzer, Proc. Phys. Soc. (London) **A68**, 525 (1955).

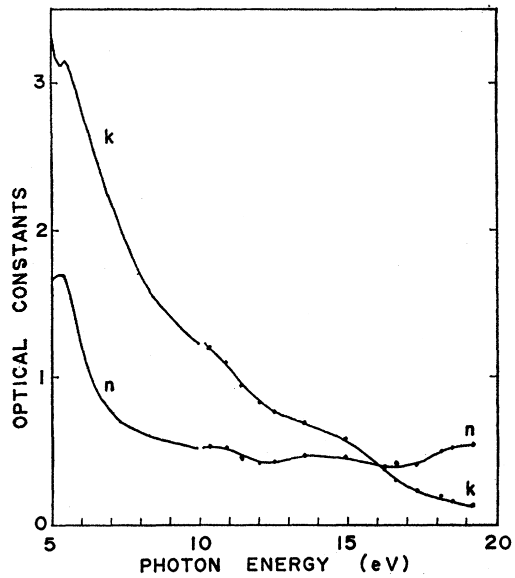

FIG. 2. The spectral dependence of the real and imaginary parts of the index of refraction. The curves below 10 eV were taken from the data published by Philipp and Taft.[1]

In Fig. 3, the spectral dependence of the real part of the dielectric constant $\epsilon'=n^2-k^2$ calculated with the values given in Fig. 2 is shown against $\hbar\omega$. The energy at which ϵ' becomes zero lies at 16.2 eV, while $\epsilon'+1=0$ occurs at 10.8 eV. In Fig. 4, the quantities $2nk/(n^2+k^2)^2$ (curve 1) and $2nk/[(n^2-k^2+1)+4n^2k^2]$ (curve 2) are plotted against $\hbar\omega$. The former has a peak at 17.3 eV instead of 16.2 eV where ϵ' becomes zero. This discrepancy might arise from the small interband damping of the plasma oscillation. Nevertheless it should be noted that the optical results are substantially in accord with those of the electronic energy loss experiments, suggesting that the characteristic loss of about 17 eV could be safely interpreted as the plasma excitation.

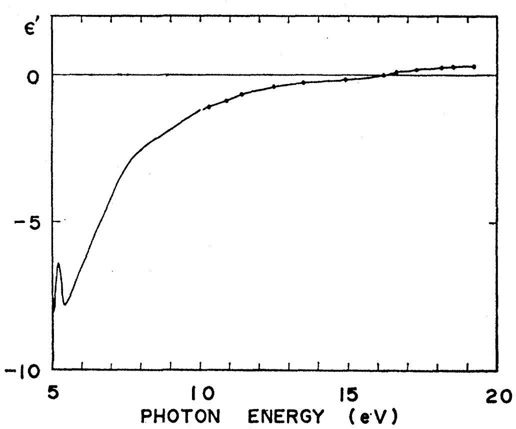

FIG. 3. The spectral dependence of the real part of the dielectric constant ϵ' of silicon in the region 5.0 to 19.2 eV. The curve below 10 eV was evaluated from the data of Philipp and Taft.[1]

The half-value width of the line observed by Marton and Leder was about 3.6 eV, in full accordance with the present result taken from Fig. 4, while the theoretical value evaluated from the relation[7] $\hbar/\tau_n=2\hbar\omega_n nk$ is 3.3 eV, assuming that $\hbar\omega_n$, the energy of a normal plasmon, is 17.3 eV.

Curve 2 shows, on the other hand, a peak at 11.6 eV instead of 10.8 eV. The half-value width estimated from Fig. 4, where the lower energy side of the curve is evaluated from the results of Philipp and Taft, is 5.2 eV, being comparable to the theoretical value 4.7 eV derived from the relation $\hbar/\tau_t=\hbar\omega_t nk$.[7]

The characteristic loss corresponding to this value was recently observed in the reflection and the Kikuchi-line spectra by the Raether's group in Hamburg.[9] They have detected a weak loss at 10.8 eV besides an intense characteristic loss of 16.9 eV. It may be tentatively assigned to the tangential plasmon as described by Kanazawa according to the above-mentioned evidence.

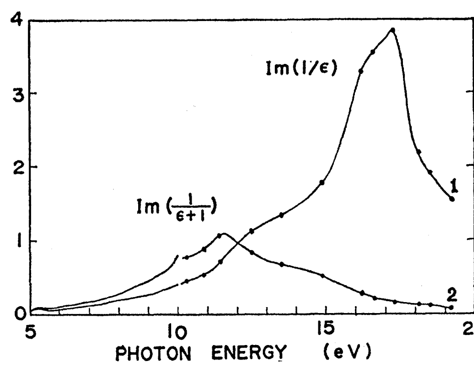

FIG. 4. The spectral dependence of the imaginary part of $1/\epsilon$ and $1/(\epsilon+1)$. Below 10 eV, the curves were evaluated from the data of Philipp and Taft.[1]

We wish to acknowledge the helpful comments of Professor H. Kanazawa. We wish to thank Asakura for assistance in running the experiment.

The present work was done as a partial fulfilment of the research project, "Study of the plasma oscillation of electrons in solids," supported by the scientific research fund of the Ministry of Education during the period 1959 to 1961.

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