FINE STRUCTURE OF THE SPECTRUM OF CHARACTERISTIC ELECTRON-ENERGY LOSSES IN GaAs

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The current of inelastically scattered electrons was differentiated with respect to the energy by an electronic method. This made it possible to detect and analyze a fine structure in the spectrum of the characteristic losses suffered by electrons of energies less than 400 eV reflected from the (110) surface of GaAs. A correlation was found between the data obtained and the results of optical measurements. It was demonstrated experimentally that the characteristic loss spectra of low-energy electrons could be used in investigations of the degree of cleanness and of the chemical composition of the surface of a solid.

INVESTIGATIONS of the spectra of the characteristic energy losses suffered by electrons during transmission through thin films or on reflection from the surface of a solid represent an important method for studying the electron structure of a solid. However, the effectiveness of this method depends strongly on the degree of refinement of the experimental technique. In the investigations described here, which were distinguished by the use of sensitive high-resolution apparatus, the use of a clean object, and a very high vacuum, we detected and analyzed a fine structure in the spectrum of the characteristic losses suffered by electrons of energies less than 400 eV reflected from the (110) surface of GaAs. Single crystals of gallium arsenide were selected on the basis of the following considerations: first, an atomically clean (110) surface of GaAs was obtained easily by cleavage in very high vacuum; secondly, $A^{III}B^{V}$ semiconducting materials were promising objects from the point of view of their emission properties; thirdly, it was interesting to compare the data obtained with the results of optical investigations.[1,2] Apart from the intrinsic interest in GaAs, we were able to demonstrate experimentally that the characteristic loss spectra of low-energy electrons could be used in qualitative analysis and, in principle, in quantitative measurements of the degree of cleanness and the chemical composition of the surface of a solid.

The experiments were carried out in an all-metal low-energy electron diffraction unit.[3] The sensitivity and the resolving power were increased by electronic differentiation of the current of inelastically scattered electrons with respect to the electron energy, as described in [4]. Figure 1 shows the basic layout of the apparatus. A beam of electrons, generated by an electron gun 1, reached a crystal 2. A smoothly varying static potential was applied, in combination with a weak alternating voltage (2 kHz frequency), to a retarding grid 4. The first and third grids (3 and 5 in Fig. 1) were grounded: they produced a field-free region and reduced the capacitance between the retarding grid and a collector screen 6. Secondary emission from the collector itself was suppressed by subjecting it to a small positive potential. Synchronous detection was used to

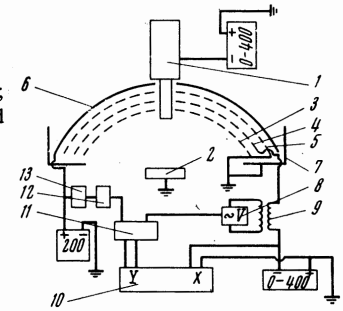

FIG. 1. Basic layout of the apparatus: 1) electron gun; 2) sample; 3) first grid; 4) second grid; 5) third grid; 6) collector screen; 7) protective screen; 8) sinusoidal oscillator; 9) transformer; 10) X-Y recorder; 11) amplifier with synchronous detector; 12) resonance filter; 13) preamplifier.

record the second-harmonic (4 kHz) component of the collector current. An automatic recorder plotted the first derivative dN/dE of the energy distribution curve of the reflected electrons.

An atomically clean surface of GaAs was obtained by cleaving a crystal in 5×10^{-10} torr vacuum. The degree of cleanness of this surface was monitored by the low-energy electron diffraction method. Figure 2 shows the diffraction pattern of 33 eV electrons of one such surface.

A part of the characteristic loss spectrum (more exactly, of dN/dE) of electrons reflected from the surface under investigation is plotted in Fig. 3. Since the spec-

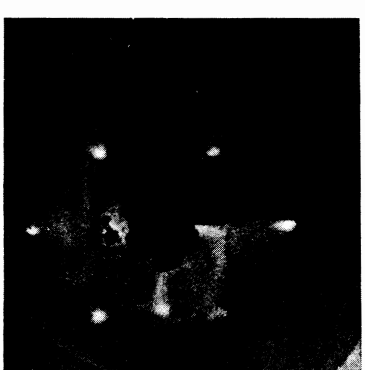

FIG. 2. Diffraction pattern of 33 eV electrons reflected from an atomically clean (110) surface of GaAs obtained by cleaving in 5×10^{-10} torr vacuum.

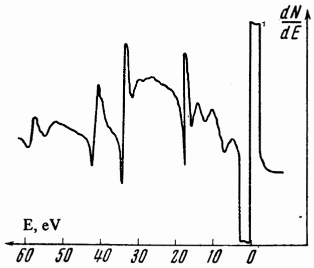

FIG. 3

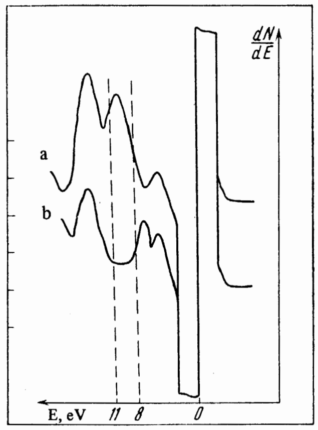

FIG. 4

FIG. 3. Part of the characteristic loss spectrum (more exactly, dN/dE) of electrons reflected from an atomically clean (110) surface of GaAs. The energy of incident electrons was E_0 = 200 eV and the amplitude of the modulating signal was 0.5V.

FIG. 4. Parts of the characteristic loss spectra of a (110) surface of GaAs cleaved in 5 $\times$ 10^{-10} torr vacuum (a) and of the same surface after storage for 8 h in 1 $\times$ 10^{-5} torr vacuum (b). The energy of incident electrons was E_0 = 200 eV and the amplitude of the modulating signal was 0.5V.

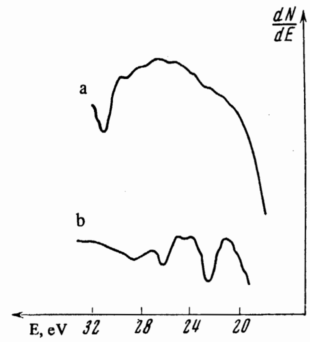

FIG. 5

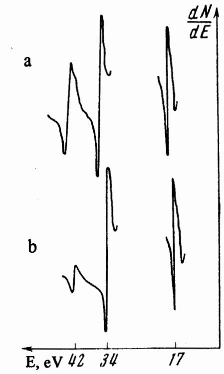

FIG. 6

FIG. 5. Parts of the characteristic loss spectra obtained in the 21-29 eV region for GaAs using different modulating signal amplitudes: a) 0.5 V; b) 0.1 V; E_0 = 200 eV.

FIG. 6. Lines in the spectrum of characteristic losses resulting from the ionization of gallium and arsenic atoms on a (110) surface of GaAs after cleaving in 5 $\times$ 10^{-10} torr vacuum (a) and after heating at T = 750°C for 5 min in 4 $\times$ 10^{-7} torr vacuum (b).

trum of the characteristic electron-energy losses of GaAs had not been investigated before, it would be interesting to consider in detail the nature of the observed lines.

The first line, corresponding to an energy loss of about 6 eV, was easily resolved at incident-electron energies below 200 eV. In all probability this line represented direct $X_5 \rightarrow X_3$ and $L_{3i} \rightarrow L_3$ band-band transitions, which had been observed clearly in optical investigations.[1]

The next two lines corresponded to energy losses of 11 and 15.5 eV. We could assume that these lines were associated with the excitation of surface and bulk plasmons. The energy loss of 15.5 eV, resulting from the excitation of bulk plasmons, was in good agreement with the position of the maximum of $-\mathrm{Im}\,\epsilon^{-1}$ (ϵ is the permittivity) deduced from the optical data for GaAs.[2] The intensity of the 11 eV line decreased with increasing incident-electron energy. We could assume that the depth of penetration of the incident electrons increased with their energy and that this reduced the relative contribution of the energy losses associated with surface plasmons.

We investigated the position of the line associated with the excitation of surface plasmons as a function of the degree of cleanness of the (110) surface of GaAs. Figure 4 shows parts of the spectrum of the characteristic energy losses of the (110) surface of GaAs cleaved in 5×10^{-10} torr vacuum (a) and of the same surface after 8 h in 1×10^{-5} torr vacuum (b). In the case of the freshly cleaved surface the line corresponding to the excitation of surface plasmons (11 eV) was typical of an interface between plasma and vacuum. Storage in poor vacuum resulted in strong adsorption of residual gases on the surface, which was indicated by a strong rise of the background and by the disappearance of reflections in low-energy electron diffraction patterns. Such storage in poor vacuum shifted the excitation line of surface plasmons to 8 eV, which was typical of an interface between plasma and an oxide layer.

The narrow strong energy-loss line at 17 eV was probably due to two processes: first, single ionization of the M_4 level of gallium atoms, and, second, two-stage losses in band-band transitions and in the excitation of surface plasmons.

The next wide maximum in the region of 21–29 eV was resolved into three lines (29, 26, and 22 eV) when the amplitude of the modulating signal was reduced, i.e., when the resolving power was increased. Figure 5 shows a part of the characteristic loss spectrum of GaAs in the region of 21–29 eV, obtained using different values of the modulating signal amplitude. It was interesting to note that the 22 eV maximum was observed also in the dependence $-\mathrm{Im}\,\epsilon^{-1} = f(E)$ deduced from the optical data.[2] The energy-loss line at 22 eV was most probably due to the excitation of bulk plasmons whose frequency changed as a result of electron transitions from the d band to the conduction band. The good agreement between the results of measurements of the characteristic losses and the low-temperature optical data was a very promising feature. The energy-loss lines at 26 and 28 eV were evidently due to two-stage processes: the 26 eV line was due to the losses resulting from the excitation of bulk and surface plasmons and the 28 eV line was due to the losses resulting from the single ionization of the M_4 level of gallium atoms and the excitation of surface plasmons.

The next energy-loss line at 34 eV was anomalous in respect of its intensity. If this line was attributed to the losses resulting from the double ionization of the M_4 level of gallium atoms, it was found that the intensity of this line should be less than that of the line at 17 eV. However, one could also assume that the 34 eV line was due to a two-stage process consisting of the single ionization of the M_4 level of gallium atoms followed by the excitation of bulk plasmons.

The narrow line at 42 eV was due to the single ionization of the M_4 level of arsenic atoms.

We found that the intensities of the characteristic loss lines representing the ionization of gallium and arsenic atoms depended on the surface concentration of these atoms. Figure 6 shows the characteristic loss lines resulting from the ionization of gallium and arsenic atoms in the (110) plane of GaAs after cleavage in 5×10^{-10} torr vacuum (a) and after heating at T = 750 °C for 5 min in 4×10^{-7} torr vacuum (b). At temperatures exceeding 650 °C we observed vigorous evaporation of arsenic atoms from the surface, whereas gallium atoms remained behind forming droplets which were easily visible under an optical microscope. The relative change in the concentrations of gallium and arsenic atoms was reflected in the intensities of the lines associated with ionization losses.

Reduction in the surface concentration of arsenic atoms resulted in lowering of the intensity of a broad energy-loss line at 57 eV. This line was probably due to a two-stage process involving the single ionization of the M_4 level of arsenic atoms followed by the excitation of bulk or surface plasmons.

A weak and very wide line at 54 eV corresponded to energy losses resulting from the triple ionization of the M_4 level of gallium atoms. However, the low intensity of this line indicated that the probability of three-stage inelastic scattering processes was low for electrons of energies below 400 eV reflected from GaAs.

In conclusion, we shall consider the possibilities of using the characteristic energy-loss spectra of slow electrons in studies of surface phenomena. Since the frequency of surface plasmons is very sensitive to the permittivity of the medium which is in contact with the given surface, an investigation of the characteristic loss lines associated with the excitation of surface plasmons may give useful information in studies of the processes of adsorption, cleaning, catalysis, growth, etc. An effective method in quantitative analysis of the chemical composition of the surface region would be provided by recording series of characteristic loss lines associated with the electron ionization of inner atomic levels.

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204