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THIN-FILM ELECTRON INTERFEROMETERS

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IT was shown during 1963 that thin-film layer inter-
ferometers for electrons could be constructed in
principle.[1,2] In such devices de Broglie waves
would interfere like light waves in a Fabry-Perot
étalon or in an interference filter. At about the same
time the observation of electron interference in a
very simple thin-film interferometer was reported
in a first brief communication.[3] A theoretical ex-
amination[4] made it clear that this effect is of great
interest for both physics and applied science. The
physical interest lies in the fact that the investigation
of electron interference resonances in thin films will
obtain information regarding the electronic proper-
ties of crystals far from the Fermi surface. The
practical interest results from the prospect of con-
structing a new class of thin-film electronic devices—
resonant tunnel diodes, triodes, tetrodes etc. The
investigation of thin films is undergoing very rapid
development, and the construction of thin-film elec-
tron interferometers has already become a completely
realistic experimental problem.

Figure 1a represents the electronic analogue of
a Fabry-Perot interferometer that was proposed
in[1,2,4]. This is a thin-film resonant tunnel diode
consisting of a conducting crystal emitter 1, a metal
collector 5, and two dielectric barriers 2 and 4 con-
nected by a thin conducting resonator 3. Figure 1, b-d
shows how the potential energy of an electron varies
depending on the barrier voltages. The emitter 1
serves as an electron reservoir, from which elec-
trons tunnel through the barriers 2 and 4 to enter the
collector 5. In the thin resonator 3, which is the most
important element of the device, the tunneling elec-
trons interfere; at a certain energy an intense de
Broglie wave is set up. Resonant tunneling (the
Ramsauer effect) thus occurs, and a system of two
identical barriers 2 and 4 in the absence of scattering
is completely transparent for resonant electrons.

We shall now attempt to predict the current-voltage
characteristic of the tunnel current j_{15} flowing from
1 to 5. Let us assume that in the resonator 3 the elec-
trons fill only the 1st level (Fig. 1b), while the 2nd
and higher levels lie above the Fermi energy level.
When the voltage V_2 is switched on (Fig. 1d) the levels
in the resonator 3 drop by the amount eV_2 with res-
pect to the Fermi level E_{F_1} in the emitter. Let the
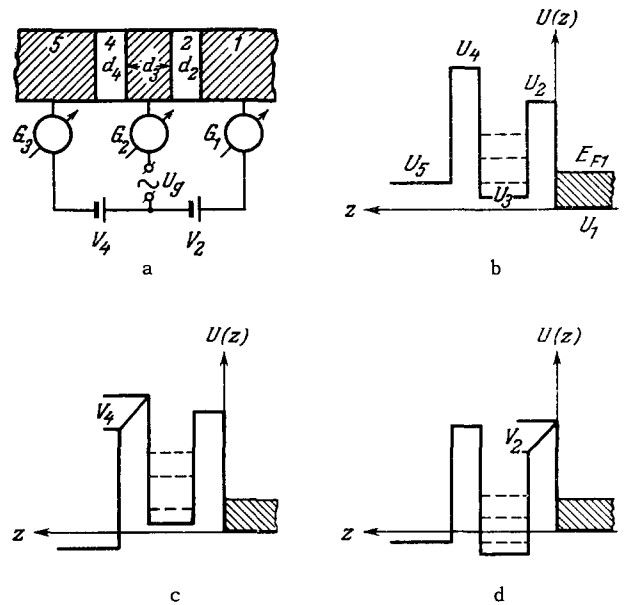electron gas in the emitter be degenerate, i.e., the

FIG. 1

emitter is a metal. As soon as the unpopulated 2nd
level of the resonator drops sufficiently to coincide
with the Fermi level E_{F_1}, resonant electron tunneling
from 1 to 5 begins; the electrons remain temporarily
on the 2nd level in the resonator. The tunnel current
j_{15} now rises steeply, but with further increase of V_2
this resonant current j_{15} soon begins to fall off ex-
ponentially, because when the 2nd level falls below
E_{F_1} the effective height of barrier 2 for resonant
electrons is elevated. However, j_{15} again rises steeply
as soon as the 3rd resonator level drops to E_{F_1} and
participates in resonant tunneling etc. Thus j_{15} will
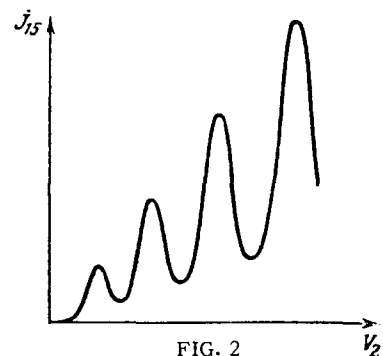oscillate as V_2 varies (Fig. 2).

FIG. 2

The separations of peaks on the current-voltage characteristic give the positions of resonator levels directly, permitting a determination of the dispersion law, i.e., the relation between electron energy and momentum. By applying an alternating voltage U_g (Fig. 1a) to the resonator 3 of a tunnel triode the resonant current j_{15} can be controlled exactly as the plate current of a vacuum tube triode is controlled by the grid voltage.

The sharpest interference resonances can occur when certain conditions are fulfilled regarding the de Broglie wavelengths and mean free paths of the conduction electrons and the character of their reflection from the resonator boundaries. The de Broglie wavelengths of conduction electrons in the resonator should be comparable with the resonator thickness d_3. Electrons of different energies and angles of incidence go from the emitter to the resonator. Therefore, as for broadband optical interference filters, in order to avoid smearing out of the interference pattern we must use resonance at the lowest normal resonator frequencies, rather than high overtones as in a Fabry-Perot optical etalon.

Good films will have a minimum thickness d_3 ~ 100 Å; conduction electrons have a de Broglie wavelength $\lambda = 12.3$ Å$/\sqrt{E_{F_1} m^*/m}$. In normal metals, where $m^*/m \sim 1$ and $E_{F_1} \sim 4$ eV, we obtain $\lambda \sim 5$ Å; thus $\lambda \ll d_3$, which is unfavorable for observing interference. In metals with small effective masses and concentrations of electrons, where $m^*/m \sim 0.1$ and $E_{F_1} \sim 0.1$ eV, we obtain $\lambda \sim 100$ Å; good resonance effects should therefore be observable in thin films. In semimetals such as Bi, where $E_{F_1} \sim 0.01$ eV and $m^*/m \sim 0.01$, we obtain $\lambda \sim 10^3$ Å; it can therefore be expected that resonance effects will begin at $d_3 \sim 10^3$ Å.

A condition is imposed on the mean free path because the intense standing wave that is required for resonant tunneling will appear in a resonator only if an electron can cross the resonator many times without scattering, being reflected specularly at the boundaries. The transverse mean free path of an electron in the resonator should therefore be very much greater than the resonator thickness: $\Lambda_\perp \gg d_3$, in conjunction with a low degree of diffuse reflection from the resonator boundaries: $\rho \ll 1$. An electron, after its resonant penetration from the emitter into the resonator, can be scattered while existing on a resonant level so that it drops to a lower resonator level. In this case the electron will usually not participate in the transverse current j_{15}, but will flow along the resonator and return to the emitter, thus contributing to the scattering current j_{13}, which flows from the emitter to the resonator and is analogous to the grid current in a vacuum tube triode. A resonant triode will operate efficiently only if j_{13} is small.

Scattering can be characterized by the effective number N_{eff} of electron round trips across the
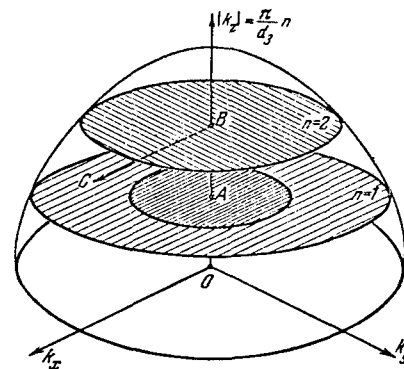

FIG. 3

resonator before it is scattered to a lower level. Scattering plays only a small part if after an average of N_{eff} collisions with barrier 4 an electron can penetrate the barrier and reach the collector, i.e., if $N_{eff}D_4 \gg 1$ (where $D_4 \sim \exp(-\sqrt{2m_4^*|E - U_4|}\,d_4/\hbar)$ is the individual transmissivity of barrier 4). The total number of electrons tunneling from 1 to 3 exhibits very little dependence on scattering in the resonator, since scattering lowers the resonance peak but compensates this by broadening the resonance band. However, the subsequent fate of electrons is completely determined by the amount of scattering. If $N_{eff}D_4 \gg 1$ electrons again tunnel through barrier 4 and participate in the transverse current j_{15}; if $N_{eff}D \ll 1$ the electrons in the resonator are scattered and contribute to the scattering current j_{13}. In the general case we have $j_{15}/j_{13} \sim N_{eff}D_4$.

The dielectric films 2 and 4 serving as barriers should be thin enough (~ 50 Å) to permit a sufficiently large probability of tunneling. Electron scattering inside the barriers should also be sufficiently small.

The electrical properties of extremely thin metallic and semiconducting films have been found in numerous investigations of recent years[5-10] to differ greatly from the properties of bulk materials. Certain specific features of the electron gas behavior in a thin resonator film 3 favor resonant tunneling. The transverse motion of an electron in a film is described by a de Broglie standing wave having nodes at the film surfaces: $\lambda_n = 2d_3/n$ ($n = 1, 2, 3, ...$). Consequently the transverse momentum and transverse energy are quantized: $|p_\perp| = 2\pi\hbar/\lambda_n = \pi\hbar n/d_3$, $E_\perp = p_\perp^2/2m^*$ $= 0.0038 \times (m/m^*) \times (100 \text{ Å}/d_3)^2\, n^2$ eV. The longitudinal energy $E_\parallel = p^2/2m^*$ remains unquantized. Quantization essentially changes the momentum distribution of electrons in a thin film. This is shown in Fig. 3, where $|k_z| = |p_\perp|/\hbar$ is the transverse component of the electron wave vector, while k_x and k_y are the longitudinal components of the wave vector. The electronic states form layers, each corresponding to a definite transverse momentum and energy. An increase of electron concentration n_0 is accompanied by an increased number of filled layers; the filling of each layer begins at the $|k_z|$ axis. For example, the filling
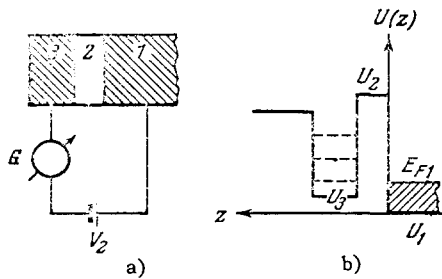
FIG. 4

of the second layer begins at the point B when the longitudinal electron energy in the first layer reaches $E_{||} = 3\pi^2\hbar^2/2m^*d_3^2$, which is the difference between the transverse energies of the first and second layers.

Using a quasi-classical concept and assuming that each electron state in a layer corresponds to a phase space cell of volume $(2\pi\hbar)^2$, we find that electrons populate only the lowest layer, while the second and higher layers remain unpopulated, when $n_0 \leq 3\pi/2d_3^3$. When $d_3 = 100$ Å this gives $n_0 < 5 \times 10^{18}$ cm^{-3}, which corresponds to the electron concentration in metals such as Bi.

The state represented by the point B in Fig. 3 describes an electron that is on the 2nd level and is moving perpendicularly to the film; here $p_\perp = 2\pi\hbar/d_3$ and $E_\perp = 2\pi^2\hbar^2/m^*d_3^3$. When scattered elastically this electron can go from point B to point C, where $p_\perp = \pi\hbar/d_3$, $E_\perp = \pi^2\hbar^2/2m^*d_3^2$, $E_{||} = 3\pi^2\hbar^2/2m^*d_3^2$, and $p_{||} = \sqrt{3}\pi\hbar/d_3$. This corresponds to scattering at the angle $\vartheta = 60°$. Elastic scattering at smaller angles is prevented by the simultaneous conservation of energy and momentum.

As a result, in a thin film we find the suppression of all small-angle scattering mechanisms, which play an important part in bulk materials. This must, in particular, reduce sharply the diffuseness of electron reflection from the film walls. We know[11] that when the mean height Δz of asperities is much smaller than their mean width Δx, giving a mildly rough surface $(4\pi\Delta z \ll \Delta x)$, the diffusion results from small-angle scattering.

Since small-angle scattering is suppressed, for electrons on the 2nd level in a thin film the diffusion coefficient is smaller than that for a single surface by a factor of the order $\exp(\sqrt{3}\Delta x/8\pi\Delta z)^2 \gg 1$. This favors resonant tunneling.

The temperature dependence of $\Lambda_\perp$ due to scattering

on acoustic phonons should also be greatly modified at low temperatures. At $T_0 = \sqrt{3\pi}\hbar v_l/kd_3$ (where v_l is the velocity of longitudinal sound and k is Boltzmann's constant) the mean phonon momentum kT_0/v_l becomes equal to the longitudinal momentum transfer $p_{||} = \sqrt{3\pi}\hbar/d_3$ that accompanies a transition from the 2nd to the 1st level in the film. As the temperature is lowered further the number of phonons capable of inducing scattering decreases as $\exp(-T_0/T)$; this should result in an exponential rise of $\Lambda_\perp$. Assuming $v_l \sim 10^5$ cm/sec and $d_3 = 100$ Å, we obtain $T_0 \sim 10°$K.

In addition to the triode already considered, other types of electron interferometers—resonant tunnel diodes and tetrodes—have been proposed. A resonant tunnel diode (Fig. 4) consists of an emitter 1, barrier 2, and resonator 3. After resonant tunneling from the emitter to the resonator, electrons are scattered and flow through the galvanometer to the resonator, thus producing a scattering current j_{13}. The current-voltage characteristic of the scattering current j_{13} resembles Fig. 2 and was observed by Kirk[3] in an Al-Al$_2$O$_3$-Al system with Al film of ~ 100 Å thickness. We note that Al is far from being the best material for observing electron interference since the de Broglie wavelength of conduction electrons in Al is too small.

A resonant tunnel tetrode (Fig. 5), which has still not been realized, would consist of an emitter 1, two resonators 3 and 5, a collector 7, and three barriers 2, 4, and 6. Complete resonant transparency of the system would require that the central barrier 4 be equivalent to the sum of the two outer barriers and that the resonant levels in the two resonators should coincide. By applying an alternating voltage V_4 to the barrier 4 we can shift the levels in resonator 5 relative to the resonator 3 and thus control the resonant current. The advantage of a tetrode over a triode lies in the fact that a tetrode would enable us to control the resonant current even when the electron gas in the emitter is nondegenerate. On the other hand, the current in a triode (Fig. 1) can be controlled only for a Fermi electron distribution in the emitter.
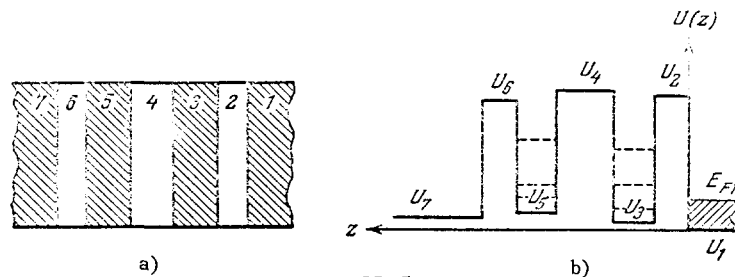
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FIG. 5

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