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Because of higher production costs, tighter loan policy and curtailed demand because of competition from synthetics, land producing henequen in the Yucatan peninsula of Mexico has been shifted to other crops. Virtually all of Mexico's henequen is consumed by a cordage industry which produces agricultural twines and rugs.

See also: Natural Fibers in the World Economy; Materials of Biological Origin: An Overview

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Size Effects in Electrical Conductors

In highly perfect metal single crystals, the mean free path of electrons at liquid helium temperatures may be as great as several millimeters. This enables electron beams to be formed and transmitted inside the metal as occurs under vacuum in numerous electron devices. However, the dispersion law—the relation between the momentum of an electron and its energy—differs for an electron in a metal and in a vacuum, so methods are needed to study electron orbits inside the metal and to measure their dimensions. For this purpose the effects determined by the relations between the dimensions of electron trajectories and those of the sample (size effects) are most suitable.

1. Direct-Current Size Effects

The simplest of size effects is the dc size effect. It is manifested as a decrease in electrical conductivity σ of thin plates and wires compared with that of a massive metal σ_0. This decrease is due to additional electron scattering by the surface of the specimen. If this scattering is diffusive, that is, if the electron is reflected at random from the surface, completely losing its drift velocity, the conductivity of a plate with thickness d is described by the expressions

$$\sigma/\sigma_0 = 1 - \frac{3}{8}\frac{l}{d} \quad (l \ll d)$$

$$\sigma/\sigma_0 = \frac{3}{4}\frac{d}{l}\ln\frac{l}{d} \quad (l \gg d) \qquad (1)$$

These expressions permit the mean free path l to be determined by measuring the dependence of σ on d. The magnitude l measured in this manner is averaged over all electrons participating in the conductivity.

More information on electrons in metals can be obtained from size effects in a magnetic field as the magnetic field changes the shape and sizes of electron trajectories. The best known of these effects is the Sondheimer effect—oscillations of the magnetoresistance of a plate in a magnetic field. Electrons which pursue helical paths about the direction of the magnetic field contribute differently to the current, depending on whether they complete a whole or a fractional number of revolutions on the path from one side of the plate to the other. This gives rise to oscillations when the magnetic field varies. The periods observed in the experiment are due to those trajectories along which the majority of electrons are travelling.

2. Radio-Frequency Size Effects

Radio-frequency size effects (RFSEs) form a specific group. When an extremal dimension of an electron orbit becomes equal to the metal plate thickness, anomalies of the surface impedance of the plate occur. They are rather small, but observable. For example, the diameter D of the orbit shown in Fig. 1 decreases proportionally to an increase in the field H. An RFSE takes place at that H value at which D becomes equal to d.

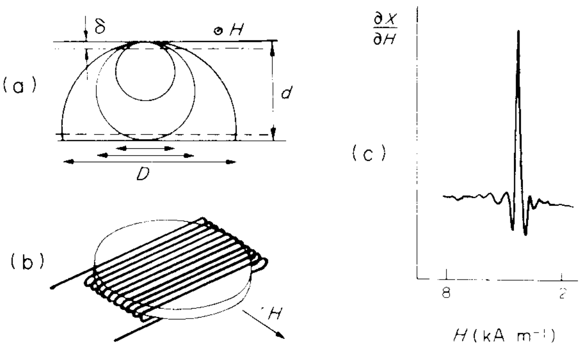

Figure 1
Observation of RFSEs: (a) different possible relations between the plate thickness d and orbit diameter D; (b) a sample in the coil; (c) an example of RFSE records

To observe RFSEs, a metallic plate is exposed to an electromagnetic field in the radio-frequency range 1–100 MHz. For this purpose it is common to place the plate inside a tuned circuit inductance coil. In this case either the Q-factor or the self-inductance of the coil, that is, the real or the imaginary part of the plate impedance, can be measured. With the aim of increasing the sensitivity, the derivatives of these quantities are often measured. Electronic equipment for these experiments is usually completely identical to that used for nuclear magnetic resonance studies.

Impedance anomalies appear in the form of narrow lines resembling resonance lines. That is why RFSE lines are sometimes called spatial resonances. The fractional width of these lines is given by $\Delta H/H \approx \delta/D$ (where δ is the skin depth, which is 10^{-3}–10^{-4} cm for the frequencies mentioned). This restricts the possibility of decreasing the plate thickness d. Fairly narrow lines may be produced when using plates with $d \gtrsim 0.1$ mm. Since the mean free path l should be at least of the order of d, this dictates requirements for the metal purity (a total impurity content of no more than 10^{-4}%) and crystal quality (an average dislocation density no greater than 10^5–$10^6\,\mathrm{cm}^{-2}$). In spite of such stringent requirements, RFSEs have been observed in alkali and noble metals (K, Cu, Ag, Au), non-transition polyvalent metals (Mg, Zn, Cd, Hg, Al, In, Ga, Sn, Pb) and semimetals (Bi, Sb) as well as in some transition metals (W, Mo, Re). At present, the fact of observing RFSEs alone certifies a high purity level for a given element.

3. *Radio-Frequency Size Effects in Multiple Fields*

A large mean free path drastically alters the electrodynamic properties of the metal. Under ordinary conditions, an electromagnetic field does not penetrate the bulk but becomes localized in a thin skin layer. In the presence of an external magnetic field, a metal with a large electron mean free path may cease to be a screen for electromagnetic radiation and become transparent to radio waves. RFSEs are intimately connected with one kind of field penetration into the metal, called ballistic penetration. The ac field is transmitted inside the metal by separate groups of electrons bunched together by the external field. Ballistic penetration results in a multilayered structure of the ac field: images of the surface current layer arise in the bulk. These current sheets are located periodically, deep into the metal. The distances between the sheets are determined by the dimensions of the orbits.

RFSEs offer the main experimental technique for the observation of ballistic penetration. Consider a plate excited on one face by an incident radiofrequency radiation with a magnetic field H parallel to the surface and circular electron orbits of diameter D. Travelling along those orbits which pass through the skin layer but do not intersect the surface, electrons increase their velocity by a small amount Δv. Each of these electrons thus becomes a carrier of part of the skin current $\Delta j = e\Delta v$. At the deepest point of its circular orbit, the electron, again travelling parallel to the surface, reproduces the velocity change $-\Delta v$ and the current $-\Delta j$. This gives rise to the current sheet at the depth $z = D$.

The thickness of this current sheet is of the same order as that of the initial skin layer $\Delta z \approx \delta$. This current sheet plays the role of the starting skin layer for the next skin image to occur at the depth $z = 2D$, and so on. As a result a chain of orbits appears, along which the electromagnetic field finds its way into the bulk.

The distance between the sheets in a certain magnetic field is defined by the shape and dimensions of the metal Fermi surface. It is always inversely proportional to H. By changing the field, the scale of the entire ac current distribution can easily be altered. The width of the current layers, however, always remains of the order of δ, so that in very large fields the layers merge.

As the field H varies, the relation $d = nD$ becomes valid in succession for $n = 1, 2, 3, \ldots$. This implies that the corresponding current sheet has reached the far side of the plate. When this occurs, the surface impedance of the plate alters and it is this that is registered as RFSE lines. The lines appear periodically in the magnetic field scale

$$H_n = nH_1 = np_F/ed \quad (n = 1, 2, 3, \ldots) \qquad (2)$$

where p_F is the diameter of the Fermi surface.

RFSEs may be related to orbits of different shape. In particular, infinite periodic trajectories with some portions in which the electron travels parallel to the surface come into play when the magnetic field is inclined to the metal surface. An example of such a trajectory is presented in Fig. 2. The meaning of the magnitude u is clear from the diagram. It serves in the same way as the diameter D in Fig. 1. Now it is the condition $d = nu$ that leads to a sequence of RFSE lines periodic in the H scale.

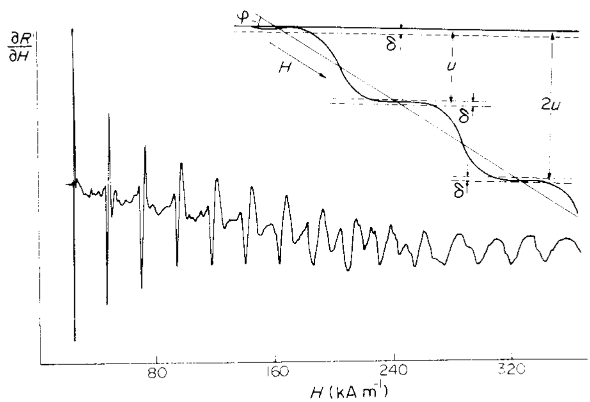

Figure 2
RFSEs in the inclined field arrangement

The distance travelled by an electron in passing from one side of the plate to the other is equal to $d \sin \varphi$. When φ is small, the distance may be much greater than d. Experimentally it has proved possible to observe RFSE lines in a tin sample 0.4 mm thick with an angle $\varphi = 1°30'$ when the length of the electron path between the faces of the plate exceeds 15 mm.

4. Applications

The shape of electron orbits is determined by the Fermi surface of the metal (see *Fermi Surfaces*). In k-space, an electron travels along the line of intersection of the Fermi surface with a plane perpendicular to the field H. The resultant curve in k-space is similar to the projection of the orbit in the crystal on the plane perpendicular to H. Therefore the information derived from RFSEs on electron orbit dimensions allows those of the Fermi surface to be determined. Thus RFSEs yield important information about the Fermi-surface geometry.

The strength A of the RFSE signal (the height of lines above the background) is proportional to the number of electrons which survive without collisions for the distance from one side of the plate to the other: $A \propto \exp(-\alpha d/l)$. Here the factor α takes into account the orbit shape. Thus measurements of line amplitude dependences on different factors, such as temperature, impurity or dislocation density, make it possible to obtain information on the interaction of electrons with different scatterers. Moreover, since each RFSE line is related to a certain orbit, by comparing these dependences for different lines, data can be obtained on the anisotropy of scattering probability at the Fermi surface. In this lies another important application of RFSEs.

See also: Electrical Conductivity of Metals and Alloys

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Slag Utilization

Extraction of a metal from an ore by heat produces both a molten metal and a slag. The latter is composed of the nonmetallic mineral material from the ores, fluxes and fuels used. Slags are also formed in refining and alloying operations on the basic metals. When produced in large quantities, slag may present a major disposal problem unless it can either be utilized as a raw material for other industries, or find direct use in construction and agricultural applications. Such uses date back some 2000 years to the Roman use of broken slag, from the iron-making Catalan forges, in road construction. Utilization of slag conserves natural resources of raw materials, avoids environmental problems in disposal of large quantities of waste materials and is of great economic value by eliminating disposal costs.

1. Iron Blast-Furnace Slag

Iron blast-furnace slag is produced in larger quantities and is used to a greater degree than any other type. Produced simultaneously with molten iron in a blast furnace, it consists primarily of silica and alumina from the iron ore combined with calcium and magnesium oxides from the flux stone. It leaves the furnaces as a liquid at about 1500 °C. Three different types of product can be produced by varying the cooling method.

Air-cooled blast-furnace slag is produced by allowing the molten slag to solidify under prevailing atmospheric conditions. It is predominantly crystalline with a cellular or vesicular structure resulting from bubbles of gases that were dissolved in the molten material. After crushing and screening to desired sizes the slag is used in the same manner as gravels and crushed stones in a great variety of applications. Principal uses are in the construction aggregate category as road bases and fills, aggregate in bituminous mixtures and Portland cement concrete, railroad ballast, roofing aggregate and sewage-plant filter media. Other applications include use as a raw material for manufacture of mineral wool, Portland cement and glass and as a soil conditioner to counteract acidity and furnish trace elements for plant growth.

Granulated blast-furnace slag is produced by quickly quenching the molten slag so as to form a glassy material with very little mineral crystallization. The most common process is quenching with water, but air or a combination of air and water may be used. The slag glass contains the same major oxides as Portland cement, but with different proportions of lime and silica. It has excellent hydraulic properties and sets in a manner similar to Portland cement when combined with a suitable activator such as calcium hydroxide. The principal use for granulated slags is as a cementitious material. Finely ground slags are used in a variety of cements, most commonly combined with Portland cement. Such cements have improved resistance to seawater and sulfate exposure. Other applications include soil and base-course stabilization, glass manufacture, agricultural liming material and production of Portland cement clinker.

Expanded or foamed slag is produced by treating the molten blast-furnace slag with limited quantities of water, less than that required for granulation. The resulting product is more cellular or vesicular in nature than the air-cooled slag and is much lighter in weight. Variations in the amount of water and the particular process used control the cooling rate, and can produce materials ranging from highly crystalline vesicular slags to glassy materials similar to the granulated slags. Various pit and machine methods have been developed to combine the molten slag and water, including a pelletizing process that makes