SECRET RESISTANCE
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It would seem that it is simpler and clearer than electrical resistance? Ohm's law, resistors, electrical losses in wires and the generation of heat from heating devices - we are familiar with all this since childhood. However, theorists have caught up so much fog in the intuitively clear phenomenon of resistance that its nature has become a secret behind seven seals. It happened when resistance was attributed to quantum phenomena that can no longer be visualized, but can only be described by formulas, renouncing common sense and taking on faith the dogmas of quantum mechanics. But the visual classical approach has by no means exhausted itself here, and often even better explains the riddles of resistance than quantum mechanics.

Electric current in metals is the directional movement of electrons - the flow of a kind of electron gas, in which electrons play the role of atoms. And just as ordinary gases experience resistance from movement through a pipeline, so electron gas flowing through a conductor is inhibited by it. That is, electrical resistance arises, the microscopic picture of which is similar to that which exists in gas. Gas atoms, colliding with each other and with the atoms of the pipeline walls, amplify their vibrations, spending part of their kinetic energy on this. This causes resistance to the gas flow and the corresponding heating of the pipeline, because the growth of atomic vibrations means an increase in temperature. It is quite natural that electrical resistance was also explained for a long time.

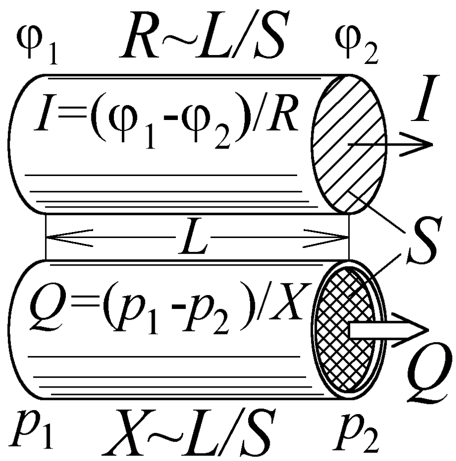

Рис. 1. Подобие силы тока I и расхода газа Q через фильтр, а также электрического R и гидродинамического X сопротивлений.

Fig. 1. Similarity of current strength I and gas flow O through the filter, and also electric R and hydrodynamic X resistances.

Electrons, gaining speed in an electric field, now and then lose some of it in collisions with metal ions, increasing their vibrations. This creates electrical resistance and releases Joule heat from the flowing current. It is not for nothing that the electric current in a conductor can be easily simulated using a gas flowing through a filter tube (Fig. 1). The gas flow through this pipe obeys exactly the same laws as the current in the conductor - it is proportional to the pressure difference (voltage), cross-sectional area S of the pipe and is inversely proportional to its length L [1]. The resistivity of such a pipe, like that of a metal, grows with increasing temperature (Fig. 2). By connecting pipes, it is possible to simulate branched electric networks (Fig. 3).

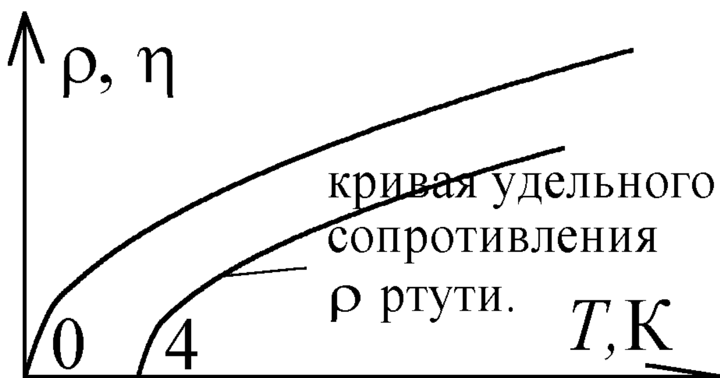

Рис. 2. Вязкость газа при снижении температуры *T* падает до нуля, как и сопротивление металла, пропорцио-нальное вязкости электронного газа.

Fig. 2. Viscosity of gas when decreasing temperature T drops to zero, as does metal resistance, proportional to the viscosity of the electron gas.

But modern scientists reject this simple and intuitive explanation of the resistance of conductors. In their opinion, the resistance is associated with the scattering of electrons by phonons - excitations of the crystal lattice of the metal [2]. After absurd photons - quanta of light, phonons - quanta of sound, quasiparticles of elastic vibrations were invented. Scientists have found that the ordered crystal lattice of metals, ideally, does not resist the movement of electrons at all. However, impurity atoms, defects and thermal vibrations of the crystal lattice violate its ideality. And the more the metal lattice is distorted, the worse it conducts current. This is precisely what quantum physics explains the temperature increase in the resistance of metals and its noticeable increase when even an insignificant impurity is introduced. It was believed that such an explanation of resistance was much better than the classical one. In fact, it is the quantum explanation that does not hold water.

$$\frac{1}{R_{об}} = \frac{1}{R_1} + \frac{1}{R_2}$$

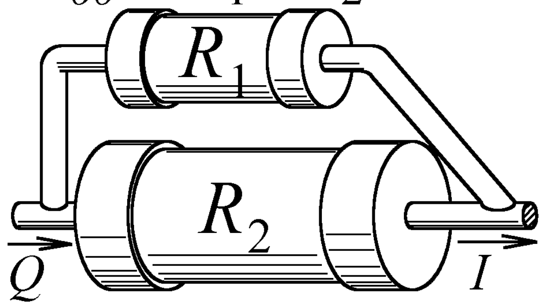

Рис.3. Общее сопротивление двух резисторов можно найти как и сопротивление двух параллельных фильтров.

Fig. 3. Total resistance of two resistors can be found as well as the resistance of two parallel filters.

Indeed, according to quantum theory, molten metals, in which the crystal lattice is completely destroyed, cannot conduct current at all. Meanwhile, they conduct current almost as well as solid, crystalline ones. Let's say liquid mercury, which we usually observe at temperatures 60 degrees above its melting point, would be a dielectric according to quantum theory. However, it is not too inferior to other metals in specific electrical conductivity (for example, lead is only 5 times), and even surpasses such metals as bismuth. And the resistance of liquid mercury changes when heated, just like that of solid metals.

In general, metals at the moment of melting increase the resistance by only one and a half to two times [3]. This alone is enough to reject as an erroneous quantum interpretation of resistance. Indeed, if, according to quantum theory, even insignificant distortions of the crystal lattice, introduced by phonons and impurity atoms, noticeably increase the resistance, then in a melt, where the order of the crystal lattice is utterly violated, the resistance grew indefinitely. But the funny thing is that some conductors, when melting, not only do not increase the resistance, but even, on the contrary, also reduce it by one and a half to two times. These are the metals bismuth, antimony, gallium and the semiconductor germanium [3, p. 126].

Such strange behavior of conductors from the point of view of quantum theory is completely mysterious. But we can easily solve this problem if we notice that all these materials - bismuth, antimony, gallium and germanium - share another anomalous property. If all other metals and semiconductors expand during melting, then these four contract, reducing their volume by several percent. This convincingly proves that the crystal lattice and its defects by themselves do not affect the resistance: the main role is played by the density of the arrangement of the atoms of the substance. And the increase in the resistance of metals during melting is associated only with their expansion - the separation of atoms. On the other hand, metals that reduce the volume during melting also reduce resistivity. For the same reason, the speed of sound in a metal and its conductivity are interconnected - both of which grow with the density of the substance.

Classically, this is easy to explain. It is known that the conductivity is proportional to the number of charge carriers - free electrons. That is why, when heated, illuminated (internal photoelectric effect), the resistance of dielectrics and semiconductors decreases: their usually bound electrons acquire speeds sufficient to detach from atoms, and begin to participate in charge transfer. In addition, the density of the metal also increases: its atoms approach each other, their electric fields overlap more and more, and electrons need less and less energy to detach from atoms and participate in charge transfer (Fig. 4). Electrons interact less and less with atoms, which, as it were, increases the width of the "pores" of the metal through which the electron gas oozes. That is why an increase in density also decreases resistance.

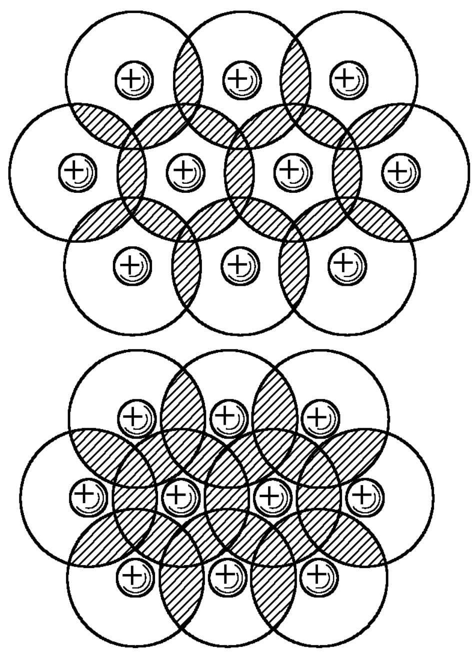

Рис.4. Чем ближе атомы в кристаллической решётке, тем шире область перекрытия их электронных оболочек (заштрихована), тем легче электроны уходят от атомов и текут потоком по расширенным каналам, порам.

Fig. 4. The closer the atoms in the crystal lattice, the dash area of overlapping their electronic shells (shaded), the it is easier for electrons to leave atoms and flow through expanded channels, pores.

And precisely, it has long been noted that metals, increasing their density under pressure, reduce resistance. Thus, the resistance of chromium under pressure *p* decreases by $6 \cdot 10^{-7}p$ of its initial value. Moreover, when compressed under enormous pressure, even dielectrics, for example, hydrogen, sulfur, become conductors. And some materials, say, silicon, germanium, go under high pressure into a superconducting state. Therefore, it is not excluded that the temperature rise in resistance is caused partly by the temperature expansion of bodies. And for metals with a negative thermal coefficient of expansion, one can expect a negative thermal coefficient of resistance. Therefore, it would be interesting to find out how the resistance of substances shrinking when heated changes changes - magnetic alloys, germanium near -243° C, plutonium above 400° C, and also chromium in the region of 37° C - the temperature near which chromium suddenly stops changing volume. However, the resistance must also change depending on the state of the electron gas. After all, the gas flow rate through the filter depends both on the size and shape of the filter pores and on the properties of the gas.

Previously, it was believed that the classical Drude theory of conductivity cannot explain why the introduction of even a small impurity into a pure metal noticeably changes its resistance. Thus, the introduction of only 1% manganese into copper increases its resistance threefold. It is clear that such a strong influence is associated with the violation of the correct crystal lattice of copper by impurity atoms. Therefore, in the quantum theory of conduction, it was considered that it is the strict periodicity of the lattice that provides conductivity. But in reality, lattice defects simply change the density of the metal and bind electrons. Everyone knows that objects laid in the correct rows take up less volume than randomly piled ones. So defects, impurity atoms, disturbing the order, expand the metal and increase its resistance. So here, too, it is not the crystal lattice itself that is important, but only its interatomic distances.

For the same reason, the specific resistances of different crystalline modifications of the same metal differ markedly. Each packing of atoms has its own density and its own interatomic distances. Their spatial arrangement also plays an important role. No wonder the resistance of a metal crystal depends on the direction in which the current flows (Fig. 5). Also, the resistance of a metal largely depends on its mechanical and heat treatment, which changes the structure and density of the metal by changing the size of the grains, crystalline modification, and the number of defects. In the classical theory of conduction, only the state of the electron gas was taken into account and almost no attention was paid to the material (filter) through which it flows. But instead of taking into account the influence of the material, physicists completely abandoned the visual picture of conductivity, replacing the classical theory with a quantum one. And although the classical approach has not yet been sufficiently developed quantitatively everywhere, quantum theory is not even qualitatively capable of correctly describing many phenomena.

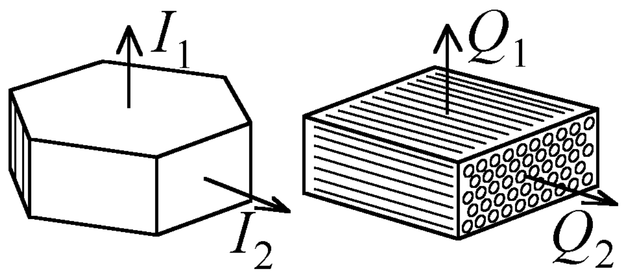

Рис. 5. Различие удельных сопротивлений вдоль разных осей кристалла, словно для тока газа вдоль и поперёк волокон фильтра.

Fig. 5. The difference in resistivity along different axes of the crystal, as if for gas flow along and across the filter fibers.

Next, we will consider the secrets of superconductivity [4]. As many have noted, its quantum theory is fundamentally flawed, which explains the extremely limited use of superconductors, which, in theory, should have revolutionized technology long ago. Therefore, great hopes have recently been pinned on the classical theory of superconductivity. Any gas, including electronic, gradually loses its viscosity with decreasing temperature (Fig. 2). Therefore, according to the classical theory, at absolute zero, the resistance should become zero: the metal will go into a superconducting state. But the real superconducting state occurs even before that. The electrons forming an electron gas, like the atoms of ordinary gases, have different velocities, obeying the Maxwellian distribution (Fig. 6). Therefore, in the metal there are always electrons with almost zero velocity. At room temperature, they are negligible. However, near absolute zero, the percentage of such electrons is already noticeable, and they are able to create currents of sufficient magnitude.

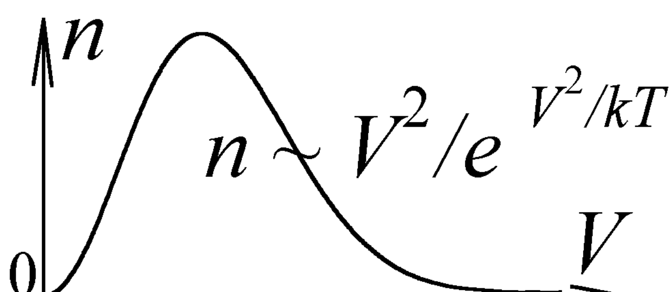

Рис. 6. Распределение частиц электронного газа по скоростям.

Fig. 6. Particle distribution electron gas at speeds.

Of course, there are more fast electrons, but, forming an electron gas of high viscosity, they create only negligible currents in comparison with the currents of slow electrons (there is also a separation in the pores of fast and slow molecules of superfluid helium [1]). Therefore, the resistance they introduce is negligible. The presence of currents of slow and fast electrons is similar to the flow of current through two parallel resistors, the first with a low resistance, the second with a large one: almost all of the current flows through the resistor R_1, and the resistance of the second is not noticeable (Fig. 3). On the other hand, it is the fast electrons that can cause negligible, but all the tangible resistance of the superconductor. It is possible that their current sets the value of critical currents and magnetic fields that destroy superconductivity.

The real snag for the quantum theory of conduction has been the discovery of superconductors, which become dielectrics at high temperatures. But according to the classical theory at low temperatures dielectrics may well be superconductors. A dielectric does not conduct current only because there are almost no free electrons in it: all electrons are bound to atoms. They thought that according to the classical theory, dielectrics do not conduct current at all [2, p. 22]. In fact, due to the spread of velocities (Fig. 6), there are always electrons in the dielectric with a velocity sufficient for separation. With an increase in the temperature and speed of electrons, more and more of them are separated from atoms and carry charge, which is associated with an increase in the conductivity of dielectrics during heating. But for dielectrics with a high degree of thermal expansion, a noticeable increase in conductivity is also possible upon cooling. After all, a cooled dielectric, decreasing in volume, brings atoms closer together, their fields overlap more and more, releasing many electrons. For these dielectrics, compression by cooling is analogous to compression by pressure, which turns them into conductors. Therefore, dielectrics at low temperatures may well open up metallic and superconducting properties.

So, the behavior of electrons in matter is fully consistent with the laws of classical mechanics and thermodynamics. Quantum mechanics, not only is "insane", also gives extremely erroneous predictions, even though theorists are used to repeating that the quantum approach is better than the classical one. In order to once again prove the adequacy of the classical description of the motion of electrons, let us finally consider the tunneling effect for them.

It is known that an electron can leave a metal only by spending energy equal to the work function A. That is why heating is required for the intense escape of electrons from the metal. This is the only way electrons appear with velocities and energies sufficient to escape from the surface (thermionic emission). In cold metals, the energy of electrons is small. But, as it turned out, electrons still leave the metal if a sufficiently strong electric field is applied from the outside. It was believed that according to the classical theory, this is impossible. Indeed, in order for the electron to gain the output energy in the electric field, it must go there a certain way, moving away from the surface. And to get out of the metal, you need the energy of the exit. It turns out to be a vicious circle: an electron could gain the required energy if it jumped over the energy barrier, but for this it needs energy [5]. But the electrons somehow come out, as if taking energy on loan and following not over the barrier, but through it, like through a tunnel. That is why this tunneling effect is considered possible only by quantum mechanics.

And yet the tunneling effect does not prove quantum fantasies about an electron blurred in the form of a wave, but admits a purely classical interpretation, if the work function is correctly interpreted. First of all, mobile electrons, even in a cold metal, now and then leave its surface, giving it a positive charge, which pulls the electrons back (Fig. 7). As a result, over the surface of any metal, a cloud of electrons soaring and falling soars - a kind of electronic atmosphere that surrounds the metal with a thin layer. This layer defines the work function. Each electron, escaping from the surface of the metal, flies into the cloud, the electrical repulsion of which creates a force F_T, pulling the electron back. The electron between the negatively charged top of the cloud and the positively charged surface appears as between the plates of a capacitor with a blocking field.

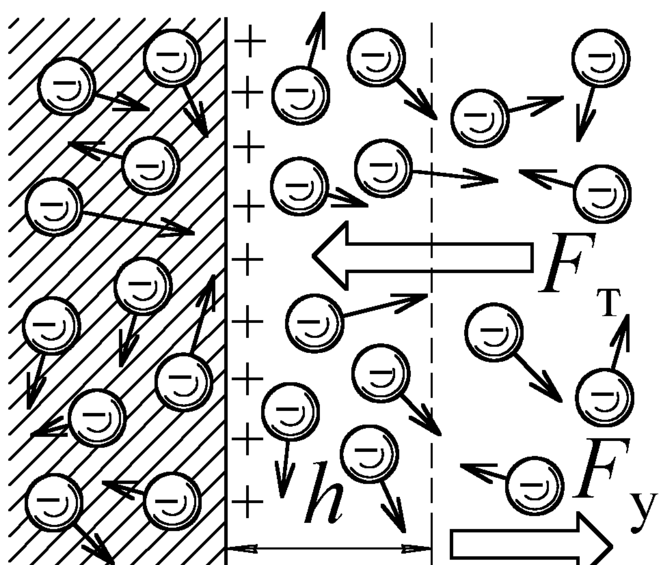

Рис. 7. Электроны, вылетевшие за границу металла, втягиваются назад. Лишь самые быстрые и ускоренные полем E покидают металл насовсем.

Fig. 7. Electrons escaping from metal border are pulled back. Only the fastest and fastest field E leave the metal for good.

In fact, a thin layer of electron gas that envelops the surface of a metal is analogous to the Earth's atmosphere, whose atoms also cannot escape into space, since for this it is necessary to overcome the earth's gravity by performing a kind of work of exit. But the speed of atoms is less than the first cosmic one, and, having taken off to a certain height, they return to the surface. Only in planets with a hot atmosphere or small size, atoms incessantly flow into space. Similar to the concentration of atoms in the atmosphere, the concentration of electrons decreases exponentially with distance from the surface. And only rare high-speed electrons reach the upper layers of the cloud.

Heating the metal accelerates the movement of electrons, and more and more of them manage to leave the metal. This is how thermionic emission arises, similar to the leakage of gas atoms from a heated atmosphere. In the case of cold emission, a different type of leakage occurs - not from an increase in the velocity of the particles of the electron gas, but from a drop in the blocking force and work function (this corresponds to the leakage of gases from small planets that are unable to hold atoms with their field). Indeed, in cold emission, the electron is not only in the locking field of the electron atmosphere, but also in the external accelerating field E, which reduces the return force F_T and allows the electrons, overcoming the attraction of the metal, to leave it for good.

Previously, it was believed that an external field is not capable of giving sufficient energy to an electron, since there is no electric field inside the metal, and the electron, according to previous ideas, could not leave the metal. In reality, the electrons fly out of the metal and on the way L gain energy EL in the field E. Thus, the external field has time to impart energy A to the electron sufficient for complete escape from the metal. A kind of tunneling effect is indeed observed here: the electron gas comes out to a certain height from the metal, without being constrained by its boundaries, as if it were really blurred. But this blur has nothing to do with the quantum-mechanical uncertainty of the position and energy of the electron, with its representation in the form of a wave. The phenomenon is of a purely classical nature, for gases and atmospheres, including electronic ones, cannot have clear boundaries. Their border is always conditional, blurred.

And numerically, the current of electrons in cold emission is consistent with the classical theory. As it was said, the concentration of electrons in the near-surface layer of the metal decreases exponentially with distance h from the boundary, similar to the density of the Earth's atmosphere with height: $n{\sim}e^{-h/kT}$. Only electrons that have passed the path $L=A/E$ in the accelerating field are capable of gaining energy A sufficient for complete flight from the metal. In other words, electrons flying to a height $h>L$ can leave the metal. Their number is easy to find by integrating their concentration $n{\sim}e^{-h/kT}$ within h from the height L to infinity. Hence, we find that the percentage of electrons from all escaped and capable of leaving the metal is proportional to $e^{-L/kT} = e^{-A/kTE}$ This dependence of the cold emission current was found experimentally [5]. By the way, the dependence of $e^{-A/kT}$ on temperature T correctly describes the thermionic emission current.

The tunneling effect seems to be explained for two metal plates separated by a thin dielectric layer. The electrons of one plate fly into the dielectric and, with its small thickness, can pass into another plate. In the absence of voltage, this flow is counterbalanced. But under voltage, a small current will flow through such a contact, the value of which grows exponentially with temperature and with a decrease in the thickness of the dielectric. The same thin electron cloud is created at the junction of two metals with different electron concentrations, which is what determines the contact potential difference.

So, the motion of electrons in matter obeys the laws of classical mechanics, and the behavior of an electron gas obeys classical aerohydrodynamics and thermodynamics (perhaps with minor corrections). Drude's classical theory of metals was inaccurate not through the fault of the classical approach, but from an underestimation of the role of the conducting medium and the electron-electron interaction. The prospects for the application of classical mechanics in materials science and solid-state physics are grandiose, but poorly understood. For too long, science has followed the dead-end path of quantum mechanics, which is the reason for its current problems and stagnation. Not only were the experimental foundations of quantum physics (photoelectric, Compton, and tunneling effects) unreliable, but quantum mechanics was unable to explain a number of phenomena at all. Therefore, only classical physics will finally make it possible to solve the problem of high-temperature superconductivity and create new materials with unique properties, not to mention making everything secret in the problem of resistance explicit and obvious.

S. Semikov

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