A Companion to Physics in the XXth century. Part 3.

Solid state physics, or more generally condensed matter physics, originated as a distinct branch of physics only about 80 years ago, but it quickly became its largest part. Metals and many other solid materials have been known since ancient times but their properties were studied by trial and error since nothing was known about their internal structure.

At the beginning of the XIXth century French scholar René Just Haüy began detailed studies of crystals. He observed the way in which they could be divided into smaller parts and from that he guessed their gross internal structure. Haüy published beautiful drawings of crystals but it was the limit of what he was able to achieve (Slide 3). Direct experimental studies of crystals could be made only after the discovery of the diffraction of X rays in 1912. Max Laue correctly guessed that the diffraction occurred on the three-dimensional grating of atoms in the crystals.

There have been many experimental observations of properties of metals, their oxides and other solid substances (Slide 4). Certain empirical relations were discovered, as e.g. the so-called Wiedemann-Franz law, that the coefficients of thermal conductivity k and electrical conductivity σ have approximately the same ratio for many metals (Slide 5).

The first theory of electrical conductivity of metals had been developed in the years 1898-1905 by Paul Drude, Hendrik Lorentz and several other physicists. The basic assumption of that theory was that the electrons inside the metals could be treated as a special gas, so that one could make use of the well developed tools of the kinetic theory of gases. This classic theory had some successes, for example the prediction that the ratio k/σ is proportional to the temperature T, which was confirmed experimentally (Slide 6). Albert Einstein was the first to give theoretical explanation for the anomalous behaviour of specific heat of several materials (such as e.g. diamond) which did not obey the empirical rule that the product of the specific heat and molecular weight was approximately constant (so-called Dulong-Petit law). Einstein rejected classical equipartition of energy, neglected free electrons in solids, and introduced quantization of lattice vibrations. His solution (indicated by E in Slide 7) was, however, far from the experimental points. Better approximations were tried by Debye (middle curve) and later by Walther Nernst and Frederick Lindemann (*NL*).

In the years just before the Ist World War important studies of semiconductors have been performed by German physicists, who introduced the term *Halbleiter* - semiconductor. Unfortunately, young brilliant Kurt Bädeker (the son of the editor of well known guidebooks) was killed in action in the first weeks of the conflict (Slide 8).

With the advent of quantum mechanics some physicists began to incorporate quantum ideas into their study of solids (Slide 9). The breakthrough occurred in 1928 when Swiss physicist Felix Bloch, who at that time was the doctoral student of Werner Heisenberg in Leipzig, published his seminal paper on the quantum mechanics of electrons in crystal lattices (Slides 10-11). It initiated the band theory of solids. In 1931 English physicist Alan Wilson proposed classification of metals, dielectrics, and semiconductors according to their band structure (Slides 13-15). At that time it was believed that semiconductors owe their electric conductivity to impurities, so that no pure substance can ever have such properties.

It took four years between the first calculation of the band structure for a crystal of infnite extent (Philip Morse, 1930) to the first calculation for real material, sodium (John Slater, 1934). In 1933 Arnold Sommerfeld and Hans Bethe published an extensive, three hundred pages long review article on the electron theory of metals. It served as „a Bible" for the first generation of people who called themselves „solid state physicists" (Slide 19).

Nevertheless, in the 1930s solid state physics remained a niche activity in comparison with the studies of atomic nuclei which attracted many researchers. During the period 1939-1945 many physicists worked on subjects connected with the war efforts, especially on very shortwave radio communication and the perfection of radar. It was found that vacuum tubes and copper-oxide rectifiers did not work well. Silicon crystal detectors were working better and became a key component of radar receivers. After the war was finished, intensive research of semiconductors attracted many physicists and engineers. One of the best centres was Bell Telephone Laboratories in Murray Hill, New Jersey.

There was urgent need for large, pure crystals of semiconductors, especially silicon and germanium. The popular method of obtaining large monocrystals was proposed already in 1916 by Polish scholar Jan Czochralski who worked at that time in Berlin. It involved placing a tiny „seed" crystal in contact with a solution or molten liquid and then withdrawing the seed very slowly. During that process additional layers of atoms gradually accumulated at the lower end. Later Czochralski became profeesor of metallurgy at Warsaw Polytechnic (Slide 21). He did not expect that his method will gain such a popularity.

Another method, called „zone refining", had been invented in Bell Laboratories by William Pfann (Slide 22). He noticed that when melted germanium solidifies, the impurities tend to remain in the liquid phase, so that the crystallized germanium is substantially purer than it was before melting. In the zone refining method a rod of germanium passes horizontally through a heating ring. The germanium segment inside the ring melts and then recrystallizes after passing beyond it. After passing through several heating rings positioned at regular intervals along the rod, the germanium crystals at the end of the process are more than 99. 99999999 percent pure - having less than one impurity atom per 10 billion germanium atoms. In picturesque expression: „less than a pinch of salt in 35 freight cars of sugar."

The transistor effect was first demonstrated on Christmas Eve, December 24, 1947 at Bell Telephone Laboratories in Murray Hill, New Jersey (Slide 23). It was an equivalent of a vacuum tube amplifier, but composed entirely from cold, solid substances. The device developed by John Bardeen and Walter Brattain was the point-contact transistor. A few weeks later William Shockley developed field-transistor. After additional experiments, the inventors were ready to show the results to the world. The invention of the transistor was announced during the big press conference in New York on June 3, 1948. The crowd of reporters had learned the origin of the name

„transistor”: „because it is a resistor or semiconductor device which can amplify electrical signals as they are transferred through it from input to output terminals”.

The first transistors had been relatively large and clumsy. Their miniaturization proceeded very quickly. In 1959 the first integrated cicuits were built independently by Jack St. Clair Kilby and Robert Noyce (Slide 24).

In Slide 26 we have a list of important events in the development of condensed matter physics. The superconductivity was discovered by accident by Heike Kamerlingh-Onnes during his experiments with liquid helium. The illustration on the left hand side in Slide 27 is his original diagram showing the resistance of mercury as a function of its temperature. At 4.2 K the resistance of mercury suddenly dropped to unmeasurably small value.

It took many years of unsuccessful efforts to develop the theory of superconductivity (Slide 28). The breakthrough came in 1957 when American physicist Leon Cooper came with the idea of „Cooper pairs”, the pairs of coupled electrons with opposite spin which can move freely through the crystal lattice. The „BCS theory” by John Bardeen, Leon Cooper and John Schrieffer provided a good description of superconductivity. The progress in finding materials which could be superconductors at higher temperatures was very slow and stopped at the niobium-germanium compound which became superconducting at 23 K. This limit was unexpectedly broken in January, 1986, when J. Georg Bednorz and K. Alex Müller of IBM in Zurich discovered supeconductivity at 30 K in a compound of barium, lanthanum, copper, and oxygen (Slide 29). Their sensational finding started the race to find materials at even higher temperatures (Slides 30-32).

The list of important events in the history of magnetism studies is shown in Slides 33 - classical physics, and 34 - quantum physics. It is worth to know that „big science”, which requires very large instruments, had a start with the great magnet built by Aimé Cotton in Paris at the beginning of the 1920s.

Richard Feynman, who gave turning point contributions to many branches of physics, provided a boost to condensed matter physics with the slogan „There’s plenty of room at the bottom” announced in 1959 (Slide 36). He pointed out the need to investigate properties of matter at the atomic level. In the following decades the studies of low dimensional structures: planar, linear (quantum wires) and zero-dimensional (quantum dots) revealed new phenomena (Slides 37-43).

There have been experiments which showed quantum-mechanical effects in a macroscale. Spectacular effect was achieved in 1999 when diffraction of large C_{60} molecules was successfully observed (Slide 44). Other effects worth mentioning were the quantization of the magnetic flux in a superconducting cylinder (Slide 45), and the stepwise behaviour of the Josephson current (Slide 46). Quantized energy states of the neutrons in the gravitational field have been recorded (Slide 47).

Slide 48 shows a list of important events in the history of modern optics. The most important success was the construction of the first ammonia maser (Slide 49), and the first ruby laser (Slide 52). The discoverer of the maser principle, Charles Townes, had to struggle with his superiors who rejected the possibility of building such a device. Slides 50-51 contain fragments of his vivid recollections. The lasers became extremely useful tools in many aspects of life (Slide 53). In 1962 Emmett Leith and Juris Upatnieks used lasers to realize optical holography. It is interesting to know that already in 1920 Polish physicist Mieczysław Wolfke envisaged the possibility of obtaining three-dimensional representation of an object with the use of coherent light. He could not realize it because of lack of intensive sources of coherent light, and his publication in „Physikalische Zeitschrift" went unnoticed. The principle of holography was reinvented in 1948 by Dennis Gabor.

Lasers were applied to develop methods of cooling and trapping atoms by light. With the use of six appropriately oriented lasers atoms could be brought nearly to rest. It opened new chapter in optical spectroscopy. Similar cooling method with the use of lasers led to the realization of the Bose-Einstein condensate in ultra-cold rubidium gas (Slides 54-55).