Technology Brief 3
Superconductivity

When an electric voltage is applied across two points in a conductor, such as copper or silver, current flows between them. The relationship between the voltage difference V and the current I is given by Ohm's law, $V = IR$, where R is the resistance of the conducting material between the two points. It is helpful to visualize the electric current as a fluid of electrons flowing through a dense forest of sturdy metal atoms, called the ***lattice***. Under the influence of the electric field (induced by the applied voltage), the electrons can attain very high instantaneous velocities, but their overall forward progress is impeded by the frequent collisions with the lattice atoms. Every time an electron collides and bounces off an atom, some of that electron's kinetic energy is transferred to the atom, causing the atom to vibrate—which heats up the material—and causing the electron to slow down. The resistance R is a measure of how much of an obstacle the resistor poses to the flow of current, as well as a measure of how much heat it generates for a given current. The power dissipated in R is I^2R if I is a dc current, and it is $\frac{1}{2}\ I^2R$ if the current is ac with an amplitude I.

Can a conductor ever have zero resistance? The answer is most definitely yes! In 1911, the Dutch physicist Heike Kamerlingh Onnes developed a refrigeration technique so powerful that it could cool helium down low enough to condense it into liquid form at 4.2 K (0 kelvin = −373 °C). Into his new liquid helium container, he immersed (among other things) mercury; he soon discovered that the resistance of a solid piece of mercury at 4.2 K was *zero*! The phenomenon, which was completely unexpected and not predicted by classical physics, was coined ***superconductivity***. According to quantum physics, many materials experience an abrupt change in behavior (called a ***phase transition***) when cooled below a certain ***critical temperature*** T_C.

Superconductors have some amazing properties. The current in a superconductor can persist with no external voltage applied. Even more interesting, currents have been observed to persist in superconductors for many years without decaying. When a magnet is brought close to the surface of a superconductor, the currents induced by the magnetic field are mirrored exactly by the superconductor (because the superconductor's resistance is zero), and consequently the magnet is repelled (**Fig. TF3-1**). This property has been used to demonstrate magnetic levitation and is the basis of some super-fast ***maglev trains*** (**Fig. TF3-2**) being used around the world. The same phenomenon is used in the ***Magnetic Resonance Imaging*** (MRI) machines that hospitals use to perform 3-D scans of organs and tissues (**Fig. TF3-3**) and in ***Superconducting Quantum Interference Devices*** (SQUIDs) to examine brain activity at high resolution.

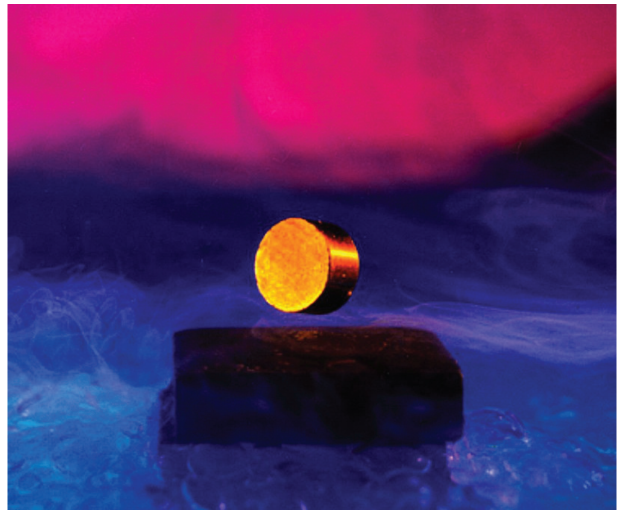

Figure TF3-1: The Meissner effect, or strong diamagnetism, seen between a high-temperature superconductor and a rare earth magnet. (Courtesy of Pacific Northwest National Laboratory.)

Figure TF3-2: Maglev train. (Courtesy of Central Japan Railway Company.)

Figure TF3-3: Magnetic Resonance Imaging machine. (Courtesy GE Healthcare.)

Superconductivity is one of the last frontiers in solid-state physics (see **Table TT3-1**). Even though the physics of low-temperature superconductors (like mercury, lead, niobium nitride, and others) is now fairly well understood, a different class of ***high-temperature superconductors*** still defies complete theoretical explanation. This class of materials was discovered in 1986 when Alex Müller and Georg Bednorz, at IBM Research Laboratory in Switzerland, created a ceramic compound that superconducted at 30 K. This discovery was followed by the discovery of other ceramics with even higher T_C values; the now-famous YBCO ceramic discovered at the University of Alabama-Huntsville (1987) has a T_C of 92 K, and the world record holder is a group of mercury-cuprate compounds with a T_C of 138 K (1993). New superconducting materials and conditions are still being found; carbon nanotubes, for example, were recently shown to have a T_C of 15 K (Hong Kong University, 2001). Are there higher-temperature superconductors? What theory will explain this higher-temperature phenomenon? Can so-called *room-temperature* superconductors exist? For engineers (like you) the challenges are just beginning: How can these materials be made into useful circuits, devices, and machines? What new designs will emerge? The race is on!

Table TT3-1: Critical temperatures.

Critical Temperature T_c [K]	Material	Type
138	$HgBa_2Ca_2Cu_3O_x$	Copper-oxide superconductors
138	$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO)	
92	$YBa_2Cu_3O_7$ (YBCO)	
55	SmFeAs	Iron-based superconductors
41	CeFeAs	
26	LaFeAs	
18	Nb_3Sn	Metallic low-temperature superconductors
10	NbTi	
9.2	Nb	
4.2	Hg (mercury)	