Superconducting Ceramics: Evaluation of Assorted Applications and Dimensions

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Abstract: All metals possess some level of electrical resistance — even those that exhibit a high degree of electrical conductivity, such as iron and copper. If this resistance can be eliminated, a single charge of electricity in a conducting loop will keep flowing indefinitely. This state is called superconductivity. Researchers are now working on ways to harness this phenomenon in exciting new applications, including superconductor powered high-speed trains, energy storage systems with superconductive coils, electricity-generating superconductive motors, and computers with superconductive elements.

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I. Introduction

Ceramics are amongst the most electrically insulating materials known. However, discoveries in the late 20th century have also shown some ceramics to be the most electrically conducting. The discovery of high temperature (above the temperature of liquid nitrogen) ceramic superconductors has changed superconductivity from an interesting curiosity to a useable technology, with particular applications in the medical field as a superconducting magnet in MRI scanners [1]. Superconductors are also used in NMR and mass spectrometers and in particle accelerators such as the large Hadron Collider [2].

Typical materials include YBCO (a mixture of the oxides of yttrium, barium and copper) and BiSSCO (a mixture of the oxides of bismuth, strontium and copper) [3]. In order to attain superconductivity, most materials must be cooled to near absolute zero (-273oC / -459oF), a state which cannot easily be achieved. However, some Fine Ceramics (also known as “advanced ceramics”) have been observed to exhibit superconductivity at significantly higher temperatures, up to about -140oC (-220oF) [4].

Though a considerable amount of research and development remains to be done before superconducting Fine Ceramics find commercial applications, positive results are highly anticipated.

Some ceramics are semiconductors. Most of these are transition metal oxides that are II-VI semiconductors, such as zinc oxide. While there are prospects of mass-producing blue LEDs from zinc oxide, ceramicists are most interested in the electrical properties that show grain boundary effects.

One of the most widely used of these is the varistor. These are devices that exhibit the property that resistance drops sharply at a certain threshold voltage. Once the voltage across the device reaches the threshold, there is a breakdown of the electrical structure in the vicinity of the grain boundaries, which results in its electrical resistance dropping from several megohms down to a few hundred ohms. The major advantage of these is that they can dissipate a lot of energy, and they self-reset – after the voltage across the device drops below the threshold, its resistance returns to being high. This makes them ideal for surge-protection applications; as there is control over the threshold voltage and energy tolerance, they find use in all sorts of applications. The best demonstration of their ability can be found in electrical substations, where they are employed to protect the infrastructure from lightning strikes. They have rapid response, are low maintenance, and do not appreciably degrade from use, making them virtually ideal devices for this application.

Semiconducting ceramics are also employed as gas sensors. When various gases are passed over a polycrystalline ceramic, its electrical resistance changes. With tuning to the possible gas mixtures, very inexpensive devices can be produced.

II. Superconductivity

The Meissner effect demonstrated by levitating a magnet above a cuprate superconductor, which is cooled by liquid nitrogen

Under some conditions, such as extremely low temperature, some ceramics exhibit high-temperature superconductivity. The exact reason for this is not known, but there are two major families of superconducting ceramics.

III. Ferroelectricity and supersets

Piezoelectricity, a link between electrical and mechanical response, is exhibited by a large number of ceramic materials, including the quartz used to measure time in watches and other electronics. Such devices use both properties of piezoelectrics, using electricity to produce a mechanical motion (powering the device) and then using this mechanical motion to produce electricity (generating a signal). The unit of time measured is the natural interval required for electricity to be converted into mechanical energy and back again [5].

The piezoelectric effect is generally stronger in materials that also exhibit pyroelectricity, and all pyroelectric materials are also piezoelectric. These materials can be used to inter convert between thermal, mechanical, or electrical energy; for instance, after synthesis in a furnace, a pyroelectric crystal allowed to cool under no applied stress generally builds up a static charge of thousands of volts. Such materials are used in motion sensors, where the tiny rise in temperature from a warm body entering the room is enough to produce a measurable voltage in the crystal.

In turn, pyroelectricity is seen most strongly in materials which also display the ferroelectric effect, in which a stable electric dipole can be oriented or reversed by applying an electrostatic field. Pyroelectricity is also a necessary consequence of ferroelectricity. This can be used to store information in ferroelectric capacitors, elements of ferroelectric RAM. The most common such materials are lead zirconate titanate and barium titanate. Aside from the uses mentioned above, their strong piezoelectric response is exploited in the design of high-frequency loudspeakers, transducers for sonar, and actuators for atomic force and scanning tunneling microscopes.

IV. Positive thermal coefficient

Increases in temperature can cause grain boundaries to suddenly become insulating in some semiconducting ceramic materials, mostly mixtures of heavy metal titanates. The critical transition temperature can be adjusted over a wide range by variations in chemistry. In such materials, current will pass through the material until joule heating brings it to the transition temperature, at which point the circuit will be broken and current flow will cease. Such ceramics are used as self-controlled heating elements in, for example, the rear-window defrost circuits of automobiles.

At the transition temperature, the material's dielectric response becomes theoretically infinite. While a lack of temperature control would rule out any practical use of the material near its critical temperature, the dielectric effect remains exceptionally strong even at much higher temperatures. Titanates with critical temperatures far below room temperature have become synonymous with "ceramic" in the context of ceramic capacitors for just this reason.

V. Superconductivity without cooling

No resistance at room temperature: The resonant excitation of oxygen oscillations (blurred) between CuO2 double layers (light blue, Cu yellowy orange, O red) with short light pulses leads to the atoms in the crystal lattice briefly shifting. Superconductivity is a remarkable phenomenon: superconductors can transport electric current without any resistance and thus without any losses whatsoever. It is already in use in some niche areas, for example as magnets for nuclear spin tomography or particle accelerators. However, the materials must be cooled to very low temperatures for this purpose. But during the past year, an experiment has provided some surprises.

With the aid of short infrared laser pulses, researchers have succeeded for the first time in making a ceramic superconducting at room temperature – albeit for only a few millionths of a microsecond. An international team, in which physicists from the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg have made crucial contributions, has now been able to present a possible explanation of the effect in the journal Nature: The scientists believe that laser pulses cause individual atoms in the crystal lattice to shift briefly and thus enhance the superconductivity. The findings could assist in the development of materials which become superconducting at significantly higher temperatures and would thus be of interest for new applications.

In the beginning, superconductivity was known only in a few metals at temperatures just above absolute zero at minus 273 degrees Celsius. Then, in the 1980s, physicists discovered a new class, based on ceramic materials. These already conduct electricity at temperatures of around minus 200 degrees Celsius without losses, and were therefore called high-temperature superconductors. One of these ceramics is the compound yttrium barium copper oxide (YBCO). It is one of the most promising materials for technical applications such as superconducting cables, motors and generators.

The YBCO crystal has a special structure: thin double layers of copper oxide alternate with thicker intermediate layers which contain barium as well as copper and oxygen. The superconductivity has its origins in the thin double layers of copper dioxide. This is where electrons can join up to form so-called Cooper pairs. These pairs can "tunnel" between the different layers, meaning they can pass through these layers like ghosts can pass through walls, figuratively speaking – a typical quantum effect. The crystal only becomes superconducting below a "critical temperature", however, as only then do the Cooper pairs tunnel not only within the double layers, but also "spirit" through the thicker layers to the next double layer. Above the critical temperature, this coupling between the double layers is missing, and the material becomes a poorly conducting metal.

In 2013, an international team working with Max Planck researcher Andrea Cavalleri discovered that when YBCO is irradiated with infrared laser pulses it briefly becomes superconducting at room temperature. The laser light had apparently modified the coupling between the double layers in the crystal. The precise mechanism remained unclear, however – until the physicists were able to solve the mystery with an experiment at the LCLS in the US, the world's most powerful X-ray laser. "We started by again sending an infrared pulse into the crystal, and this excited certain atoms to oscillate," explains Max Planck physicist Roman Mankowsky, lead author of the current Nature study. "A short time later, we followed it with a short X-ray pulse in order to measure the precise crystal structure of the excited crystal."

The result: The infrared pulse had not only excited the atoms to oscillate, but had also shifted their position in the crystal as well. This briefly made the copper dioxide double layers thicker - by two picometres, or one hundredth of an atomic diameter - and the layer between them became thinner by the same amount. This in turn increased the quantum coupling between the double layers to such an extent that the crystal became superconducting at room temperature for a few picoseconds.

On the one hand, the new result helps to refine the still incomplete theory of high-temperature superconductors. "On the other, it could assist materials scientists to develop new superconductors with higher critical temperatures," says Mankowsky. "And ultimately to reach the dream of a superconductor that operates at room temperature and needs no cooling at all." Until now, superconducting magnets, motors and cables must be cooled to temperatures far below zero with liquid nitrogen or helium. If this complex cooling were no longer necessary, it would mean a breakthrough for this technology.

Conductive ceramics, advanced industrial materials that, owing to modifications in their structure, serve as electrical conductors [6].

In addition to the well-known physical properties of ceramic materials—hardness, compressive strength, brittleness—there is the property of electric resistivity. Most ceramics resist the flow of electric current, and for this reason ceramic materials such as porcelain have traditionally been made into electric insulators. Some ceramics, however, are excellent conductors of electricity. Most of these conductors are advanced ceramics, modern materials whose properties are modified through precise control over their fabrication from powders into products. The properties and manufacture of advanced ceramics are described in the article advanced ceramics. This article offers a survey of the properties and applications of several electrically conductive advanced ceramics.

The causes of resistivity in most ceramics are described in the article ceramic composition and properties. For the purposes of this article, the origins of conductivity in ceramics may be explained briefly. Electric conductivity in ceramics, as in most materials, is of two types: electronic and ionic. Electronic conduction is the passage of free electrons through a material. In ceramics the ionic bonds holding the atoms together do not allow for free electrons. However, in some cases impurities of differing valence (that is, possessing different numbers of bonding electrons) may be included in the material, and these impurities may act as donors or acceptors of electrons. In other cases transition metals or rare-earth elements of varying valency may be included; these impurities may act as centres for polarons—species of electrons that create small regions of local polarization as they move from atom to atom. Electronically conductive ceramics are used as resistors, electrodes, and heating elements.

Ionic conduction consists of the transit of ions (atoms of positive or negative charge) from one site to another via point defects called vacancies in the crystal lattice. At normal ambient temperatures very little ion hopping takes place, since the atoms are at relatively low energy states. At high temperatures, however, vacancies become mobile, and certain ceramics exhibit what is known as fast ionic conduction. These ceramics are especially useful in gas sensors, fuel cells, and batteries.

Semimetallic ceramic conductors have the highest conductivities of all but superconducting ceramics (described below). Examples of semimetallic ceramics are lead oxide (PbO), ruthenium dioxide (RuO_2), bismuth ruthenate ($Bi_2Ru_2O_7$), and bismuth iridate ($Bi_2Ir_2O_7$). Like metals, these materials have overlapping electron energy bands and are therefore excellent electronic conductors. They are used as “inks” for screen printing resistors into thick-film microcircuits. Inks are pulverized conductor and glaze particles dispersed in suitable organics, which impart the flow properties necessary for screen printing. On firing, the organics burn out as the glazes fuse. By varying the amount of conductor particles, it is possible to produce wide variations in the resistance of thick films.

Ceramics based upon mixtures of indium oxide (In_2O_3) and tin oxide (SnO_2)—referred to in the electronics industry as indium tin oxide (ITO)—are outstanding electronic conductors, and they have the added virtue of being optically transparent. Conductivity and transparency arise from the combination of a large band gap and the incorporation of sufficient electron donors. There is thus an optimal electron concentration to maximize both electronic conductivity and optical transmission. ITO sees extensive application as thin transparent electrodes for solar cells and for liquid-crystal displays such as those employed in laptop computer screens. ITO also is employed as a thin-film resistor in integrated circuits. For these applications it is applied by standard thin-film deposition and photolithographic techniques.

VI. Heating Elements

A longstanding use of conductive ceramics is as heating elements for electric heaters and electrically heated furnaces. Conductive ceramics are especially effective at elevated temperatures and in oxidizing environments where oxidation-resistant metal alloys fail. Examples of electrode ceramics and their temperatures of maximum use in air are shown in Table 1. Each material has a unique conduction mechanism. Silicon carbide (SiC) normally is a semiconductor; suitably doped, however, it is a good conductor. Both SiC and molybdenum disilicide ($MoSi_2$) form protective silica-glass surface layers, which protect them from oxidation in oxidizing atmospheres. $MoSi_2$ is a semimetal with a high conductivity. Lanthanum chromite ($LaCr_2O_4$) is a small polaron conductor; substituting alkaline-earth ions (e.g., calcium, or Ca^{2+}) for La^{3+} results in an equal proportion of Cr^{3+} being converted to Cr^{4+}. Hopping of electrons between the two states of Cr ions yields high conductivity, especially at elevated temperatures.

Table 1. Heating element ceramics

ceramic material		temperature of maximum use in air
common name	chemical formula	(°C/°F)
silicon carbide	SiC	1,500/2,730
molybdenum disilicide	$MoSi_2$	1,800/3,270
lanthanum chromite	$LaCr_2O_4$	1,800/3,270
zirconia	ZrO_2	2,200/3,630

Superconductivity is the complete disappearance of electric resistance in materials that are cooled to extremely low temperatures. The temperature at which resistance ceases is referred to as the transition temperature, or critical temperature (Tc). Tc is usually measured in degrees kelvin (K)—0 K being absolute zero, the temperature at which all atomic motion ceases. The best ceramic conductors are the so-called high Tc superconductors, materials that lose their resistance at much higher critical temperatures than their metal alloy counterparts. Most high Tc ceramics are layered structures, with two-dimensional copper-oxygen sheets along which superconduction takes place. The first of these was discovered in 1986 by the Swiss researchers J. Georg Bednorz and Karl Alex Müller. Within a year an yttrium barium copper oxide ceramic, $YBa_2Cu_3O_7$, had been discovered to have a Tc higher than 77 K, the boiling point of nitrogen (−195.8° C, or −320.4° F). This finding raised the possibility of practical superconductors being cooled by liquid nitrogen—as opposed to conventional superconducting materials, which have to be cooled by more expensive liquid helium.

Although still higher transition temperatures have since been achieved, ceramic superconductors are difficult to process (in contrast to metal alloy superconductors), and they are notoriously brittle—properties that have limited their application. In hospitals and clinics small superconducting magnets are used in magnetic resonance imaging (MRI) apparatuses, where they generate the large magnetic fields necessary to excite and then image atomic nuclei in body tissues. Potential applications include wires for highly efficient superconducting magnets and low-loss electric power transmission lines, as well as advanced devices such as Josephson junctions and so-called SQUIDs (superconducting quantum interference devices). Josephson junctions, formed at contacts between two superconductors, can convert a direct voltage into an alternating current whose frequency rises with applied voltage. Frequencies in the superhigh frequency (SHF) range can be achieved. SQUIDs are highly sensitive magnetic-field sensors based on a superconducting ring with a weak link, a point where the material reverts to its normal, nonsuperconducting state at a small current relative to the rest of the ring. SQUIDs are widely used in geophysics for measuring magnetic field oscillations of the Earth. They also are used to record magnetograms of organs in the human body.

VII. Conclusion

Conductive ceramics are only one of several types of electroceramics. For a survey of all advanced electromagnetic applications. The causes of resistivity in most ceramics are described in the article ceramic composition and properties. For the purposes of this article, the origins of conductivity in ceramics may be explained briefly. Electric conductivity in ceramics, as in most materials, is of two types: electronic and ionic. Electronic conduction is the passage of free electrons through a material. In ceramics the ionic bonds holding the atoms together do not allow for free electrons. However, in some cases impurities of differing valence (that is, possessing different numbers of bonding electrons) may be included in the material, and these impurities may act as donors or acceptors of electrons. In other cases transition metals or rare-earth elements of varying valency may be included; these impurities may act as centres for polarons—species of electrons that create small regions of local polarization as they move from atom to atom. Electronically conductive ceramics are used as resistors, electrodes, and heating elements.

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