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Promises and realities in the application of superconductivity to energy issues

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In this paper we review the recent progress on the application of superconductivity to the field of energy conservation, and follow this with examples of detailed materials analysis techniques from our laboratory.

Keywords: Superconductivity; power lines

En este artículo se revisan los avances recientes sobre la aplicación de la superconductividad al campo de la conservación de energía y se dan ejemplos detallados de las técnicas de análisis de materiales usadas en nuestro laboratorio

Descriptores: Superconductividad; líneas de potencia

PACS: 74.90.+n

1. Introduction

Since its discovery in 1911 by Kammerling Onnes [1], superconductivity has been perceived as the next-generation technology for the efficient distribution of electrical power [2]. This is because a primary property of the superconductor is that it has zero resistance to the flow of electricity [3]. Unfortunately it was not until the middle of this century that practical materials were found to make this possible, albeit with substantial cost due to the need for refrigeration below 10 Kelvin. The cost was indeed prohibitive enough that the impressive demonstrations done in many laboratories did not become accepted commercial products for power generation or distribution. The discovery in 1986 by Bednorz and Mueller [4] of a new class of materials that become superconducting at higher temperatures, now as high as 150 Kelvin [5], was therefore received with great excitement and enthusiasm [6].

Unfortunately the new materials, dubbed "high temperature superconductors" or HTS, are all ceramics with a perovskite structure, which renders them too brittle to make wire. Since wire is the first building block for many applications of superconductors, the progress for widespread commercial applications has been disappointingly slow. Nevertheless, the substantial worldwide effort to make useful wire with these materials is starting to pay off, and demonstration projects are now starting to go out of the laboratory into the "real world". The best example of this is a superconducting power line that will be installed in the power grid of Detroit and should be operational in the year 2000, as described below.

2. Applications of superconductivity

The traditional classification of the applications of superconductivity makes a division between small-scale and large scale, as follows:

A) Small scale

1) SQUIDs (Superconducting Quantum Interference Devices)
    - Magnetometers
    - Ammeters
    - Voltmeters
    - Transducers

2) Voltage standards, oscillators

3) Amplifiers, mixers; bolometers

4) Analog signal processing (Filters, convolvers, striplines)

5) Logic
    - Small: Analog/Digital converters, logic gates
    - Large: Computers (Interconnects, memory, logic)

B) Large scale

1) Power lines (DC preferably)

2) Magnets laboratory ($>$ 20 Tesla) high energy physics
    - MRI (Magnetic Resonance Imaging)
    - Power generators, electric motors
    - Levitation: trains, etc.
    - Power storage
    - Ship propulsion
    - Fusion reactors

It should be noted that all of the applications listed above, except for fusion, have been demonstrated at least in laboratory prototypes and that many are commercially available. Some are already using high temperature superconductors.

From the list above one can see that "small-scale" refers mostly to size and involves electronic applications and sensors. These devices are used because they provide better performance than other technologies or because they are the only device that can provide a certain type of measurement. While the devices themselves use very little energy, usually the energy costs associated with refrigeration make the overall energy use higher than that of other technologies. For this reason small-scale devices will not be discussed here, except to say that there has been recent success in the application of high temperature superconductors for commercial cellular phone transmitter/receiver units [7].

Many of the large scale applications listed above provide energy savings even when one takes into account the energy used for refrigeration. In some cases superconductivity provides capabilities that are not available with any other technology, such as magnetic fields over seven Tesla. Clearly, superconductors would have replaced competing technologies by now except for their higher cost and the added complexity of refrigeration. Since the generation and transmission of electrical power with superconducting technologies promise the largest energy savings, these two topics will be discussed in more detail.

3. Superconducting generators

The electromechanical efficiency of generators currently used in power plants is about 98%, so improving this to nearly 100 percent with superconducting technology does not represent a very attractive gain. On the other hand, in applications such as nuclear power plants, the reduction in size and weight provided by a superconducting generator may be attractive, as well as the better response to transients and fault current conditions. A 300 MVA generator was designed by EPRI and Westinghouse as a first step towards the construction of 1000-4000 MVA units [8]. Unfortunately the project was suspended due to decreased interest in nuclear power generation [2].

4. Superconducting power lines

A prototype for a nearly losless AC power line based on low Tc superconductors was designed and built at Brookhaven National Laboratories [9]. While it is clear that this technology works, the cost and complexity of obtaining and maintaining temperatures below 10 Kelvin makes it impractical, specially in the absence of nuclear power plants. The discovery of superconductors with transition temperatures up to 132 Kelvin (155 Kelvin under pressure) [5] was therefore very exciting because it greatly reduces the refrigeration requirements.

Unfortunately the new superconductor are ceramics, which means that they are too brittle to make wire. Nevertheless, the commercial importance of superconducting wire has resulted in intense worldwide efforts to solve this problem, and it is encouraging to see the first commercial products coming from these efforts [10]. The ductility problem has been addressed by using silver as a matrix which is made superconducting by a high density of $Bi_2Sr_2Ca_2Cu_3O_8$ superconducting particles contained within it. This has the advantage that the superconducting particles can be cheaply produced by bulk techniques, but the disadvantage of the high cost of silver and the reduction of superconducting properties due to the use of the non-superconducting metal. An alternative approach, which is not yet commercially available, is to use a cheaper substrate such as a nickel or Hastelloy tape and to coat it with buffer layers and superconducting layers by thin-film techniques. Unfortunately this approach is currently too expensive to produce large quantities of wire.

As pointed out by Grant [11], the silver tape technology will have to come down to a cost of about $10 per meter for 1 kA capacity in order to be truly attractive for power transmission over long distances. On the other hand, there are special situations such as the replacement of critical sections of a power grid in urban environments. In this case the ability of superconducting technology to deliver higher power densities in existing buried ducts may be attractive despite the higher cost of the wire and its refrigeration requirements. A real-life test of this concept is scheduled to go online in the year 2000 by putting a superconducting power line in a downtown substation in Detroit.

The Detroit substation test will use $Bi_2Sr_2Ca_2Cu_3O_8$ /silver superconducting tapes wound into cables. The power line will carry 3000 A (rms) in a three-phase configuration and will fit into an existing 10 cm diameter buried duct. It will replace a 30-year-old copper conductor, yet it will provide 2.5 times larger power capacity within the same constrained space.

As with any other technology, the real impact will be determined by the overall costs and the demonstrated performance. This first test is therefore critical for the future implementations of superconducting technology in the distribution of electrical power.

5. Magnetic levitation

Besides zero resistance, superconductors have the unusual property that they expel magnetic flux from their interior, as discovered by Meissner and Oschenfeld in 1933 [12]. This property can provide a simple explanation for the popular demonstration of the levitation of magnets on top of a superconductor: as the superconductor expels the magnetic flux it repels the source of that flux, namely the magnet [13]. Perhaps the most impressive demonstration of this effect is the levitation of a sumo wrestler with a total mass of 300 kg [14]. Observing these kinds of demonstrations immediately brings to mind applications such as frictionless bearings [15] and levitated trains.

In the case of trains, however, the physics of the levitation effect is the repulsion due to Eddy currents in the normal metal rails; the superconductor only provides a large magnetic field. Very recently an impressive record has been reported: a levitated train (MagLev) with superconducting magnets has achieved a record speed of 552 kilometers per hour (this demonstration includes passengers in a 5-car train, while the previous record was an unmaned train with two cars) [16]. While this is a beautiful and impressive technology, there are criticisms from the economic and practical point of view [17], arguing that wheeled trains are now operating up to 300 km/h and that airplane fares are going down, so that the extra costs of the superconducting technology may not make sense. As always, this will eventually be determined by market forces.

6. Materials characterization

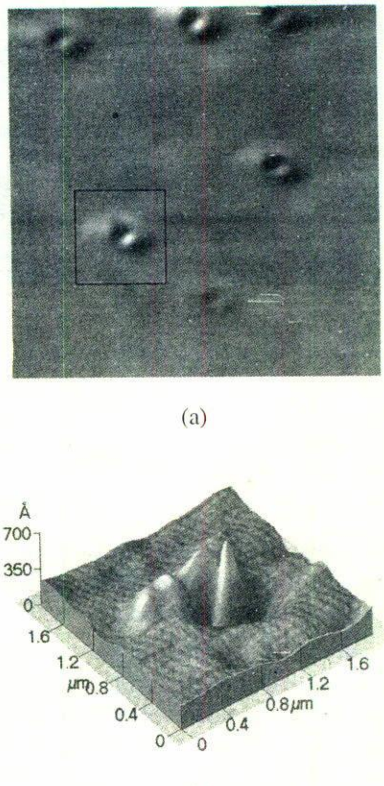
The discovery, optimization, and commercialization of superconducting materials has always used a wide array of tools to determine composition, structure, and other properties of the materials being developed. These techniques range from the simple and inexpensive, such as the measurement of resistivity, to the sophisticated and costly, such as chemical and structural analysis by Rutherford back scattering (RBS). The author has a special interest in scanning probe techniques, where a microscopic probe is scanned over the superconducting surface, therefore these techniques will be briefly reviewed here. A more comprehensive review of this family of techniques has been published very recently [18].

7. Magnetic force microscope

The magnetic force microscope (MFM) is not the first of the scanning probe techniques to be applied to superconductors, but it is perhaps the easiest to understand. The basic idea is to scan a microscopic magnet over the surface of the superconductor. The tiny magnet is levitated on top of the superconductor in much the same way as the Sumo wrestler was levitated in the demonstration described above. As the superconducting properties change over the surface, this levitation changes, thus providing a spatial map of the superconducting properties.

The microscopic magnet used in MFM is formed by coating the microscopic tip of an atomic force microscope (AFM) with a magnetic thin film, such as iron. The AFM tip is supported by a microfabricated cantilever and the interaction of the tip with any surface is measured by monitoring the deflection of the cantilever. This is usually done by optical methods, but in the case of low temperature and vacuum environments it is preferable to use a stress sensor that is built into the microfabricated cantilever [19].

One of the most interesting applications of MFM on superconductors is to image vortices. Superconducting vortices are very interesting because they provide a mechanism for type II superconductors to survive very large applied fields, by letting the magnetic flux penetrate at one point (the center of the vortex). The rest of the superconductor is shielded from this flux by circulating superconducting currents, which brings to mind the picture of a tornado or a vortex. An example of MFM images of vortices is shown in Fig. 1.



(a)

(b)

FIGURE 1. (a) Noncontact LT MFM image, 6.1μ m on a side, of a $YBa_2Cu_3O_{7-x}$ film showing vortices with an asymmetric shape. The gray scale spans 61 nm. (b) 3D display of the vortex marked in (a). Reproduced from Ref. 19.

Another application of MFM to superconductors is to observe the penetration of magnetic flux on scales larger than that of vortices. As shown in Fig. 2, this essentially shows the weakest points in a superconducting thin-film. Not surprisingly, the magnetic flux first penetrates through the grain boundaries of this film.

8. Scanning tunneling microscope

The scanning tunneling microscope (STM) [20] is the most famous of the scanning probe techniques, although it is historically not the first one. Nevertheless, the great success of the STM resulted in many other techniques based on similar ideas, such as the AFM and MFM mentioned above. For this reason the STM is regarded as the founding technique for most of the scanning probe microscopies.

The STM is based on the quantum mechanical tunneling of electrons from a sharp conducting tip to the surface of a conducting sample. The tunneling process is strongly dependent on the tip-sample distance, at the rate of one order of

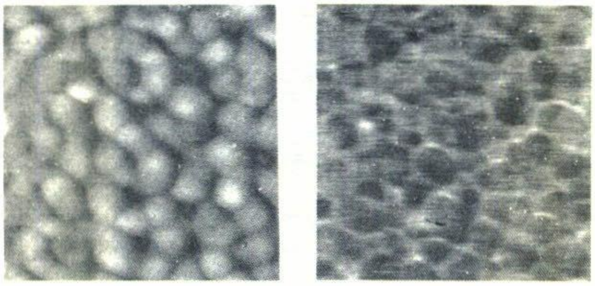


FIGURE 2. This shows the topography (right image) and the magnetic image (left) of the same 1 μm × 1 μm area of a YBCO thin film. The latter shows the penetration of magnetic flux through the grain boundaries. Reproduced from Ref. 18.

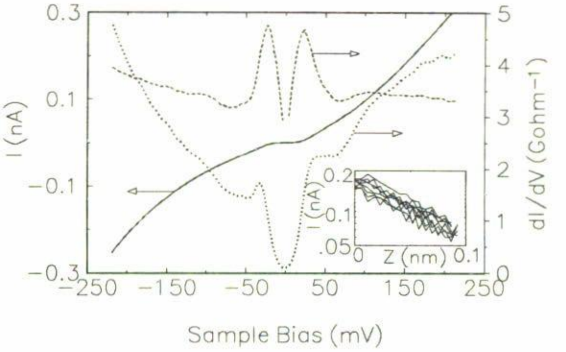


FIGURE 3. The solid curve is the average of 128 I-V curves taken at the same location, at 20 K (4 mV, 9 pA offset subtracted). The dotted curve is the conductance dI/dV. The dashed curve is $R(V) = (dI/dV)/(I/V)1/2$; the peak positions give $0.9\ \Delta$. The inset shows the exponential dependence of the tunnel current (log scale) on height (linear scale) as the tip traversed the 0.1 nm path 8 times. Reproduced from Ref. 18.

magnitude per Angstrom for clean metals, making the initial implementation of the technique difficult, but at the same time giving it unsurpassed resolution.

The first demonstration [21] of the capabilities of the STM to measure superconducting surfaces used some of the most sophisticated superconductors available at the time this technique was first developed, namely the A-15 materials such as Nb_3Sn. The A-15 superconductors had the highest transition temperatures, in the range of 18–23 Kelvin.

As soon as the high temperature superconductors were discovered, the STM was used to characterize them, particularly to measure the superconducting gap [22, 23]. This gap is a forbidden zone in the electronic density of states of the superconductor, and is one of the most important parameters for this material. To measure the gap the STM is used in the spectroscopic mode: the tip is fixed over the location of interest, the voltage is ramped and the tunneling current is recorded (the resulting data is called an IV curve). An example is shown in Fig. 3. The flat region of the IV curve at low bias voltage indicates that little current flows, thus implying that there is an energy gap. This is more clearly seen in thein the numerical derivative (dI/dV, which is the differential conductance) by a big dip at low bias voltage.

More recently, computers have made it possible to take a large amount of spectroscopic data over a regular mesh of points on the surface [24]. the huge amount of data obtained can be shown as images of the current at fixed voltages [24], or the differential conductance can be computed and shown as an image over the surface [25, 26], as shown in Fig. 4. This is a powerful technique because the map of the differential conductance obtained at a voltage near the gap (22 mV in this case) gives a very clear visual image of the spatial distribution of the gap. The dark regions and this figure have no gap, essentially behaving as a normal metal, while the bright regions have a fully developed gap. Interestingly, the boundary between the gap and non-gap to regions is a straight line and the crossover from one region to the other takes place in about 20 nm (Fig. 4b), which is consistent with the coherence length of the superconductor in the a-b plane.

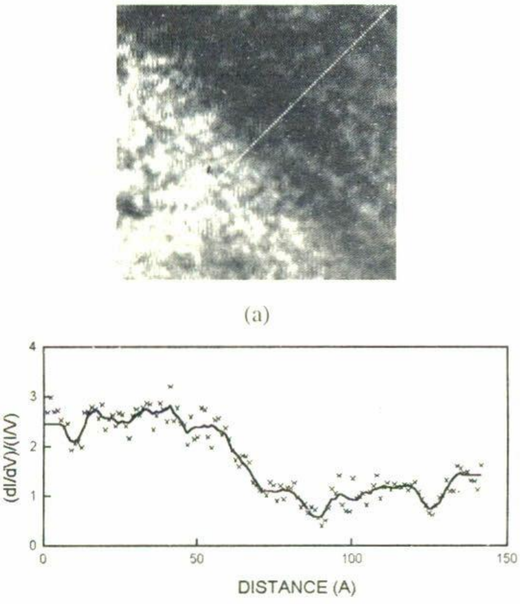


FIGURE 4. Spatial map (a) of the logarithmic derivative $[dI/dV]/[I/V]$ at $V = -22.5$ mV, obtained by subtracting the current image at $V = -20$ mV from the one at $V = -25$ mV and dividing by the average of the two. A slight spatial averaging is done to reduce the noise introduced by taking differences. The cross section (b) is taken through the diagonal shown in the image. The vertical scale in the cross-section is arbitrary, so we have normalized it to 1 in the normal region. Reproduced from Refs. 25 and 26.

The STM is well-known for the beautiful images it has produced on many surfaces with exquisite detail down to the atomic scale. For $YBa_2Cu_3O_{7-x}$ we have found that the best method to prepare its surface is to cleave single crystals at low temperature and to take STM data below 30 Kelvin, without letting the sample warmup at any time. In this case one can

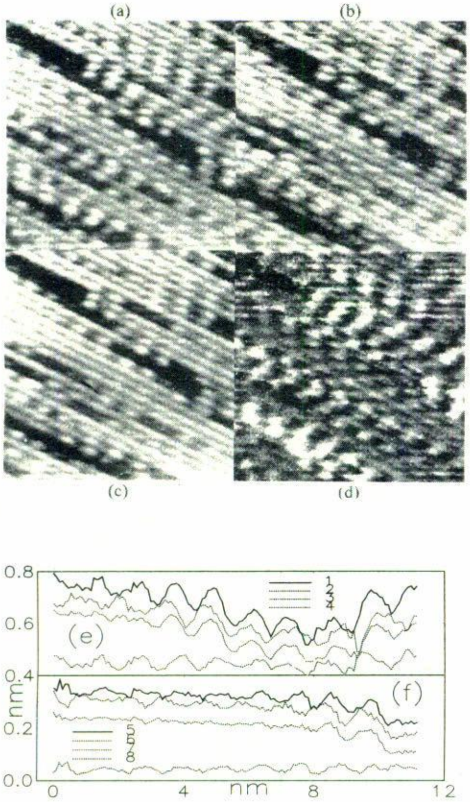


FIGURE 5. Reversed-bias images of the CuO chain layer of YBCO. The sample bias is (a) 240 mV and (b) −240 mV; (c) is the average of (a) and (b), and (d) is their difference. Images are 10 nm on a side, and the average tunneling current is 40 pA. (e) and (f) are cross-sectional plots from (a)–(d), taken along the lines marked on (c): plots in (e) were taken along the upper line, whereas those in (f) were taken along the lower line. The correspondence of curves to images is: (a) 1 and 5; b) 2; (c) 3 and 7; (d) 4and 8. Reproduced from Ref. 27.

clearly observe the CuO chains of this compound, seen as the diagonal lines in Fig. 5. A surprising discovery from our STM images was the observation of a superstructure or modulation running along the chains [27, 28]. This is not simply topography because these modulations reverse when one reverses the tunneling direction. Our discovery was confirmed by neutron diffraction [29], which also showed that the same phenomenon occurs in the bulk of the crystal.

9. Conclusions

The commercial impact of superconductivity has been substantial, in the order of a billion dollars per year, most of which is based on the low Tc superconductors. Therefore one can say that superconductivity has fulfilled many of the promises that were made since its discovery in 1911. A good example is the use of superconducting magnets for magnetic resonance imaging (MRI), which is now available in many hospitals around the world. Nevertheless, the impact would be much higher if high temperature superconductors could be made into practical wires at a reasonable cost. Such wires would have great usefulness in the generation, transmission, and storage of electricity, as well as the generation of large magnetic fields for levitation and many other applications. The first real-life demonstration of a superconducting power line, to be installed in downtown Detroit next year, will hopefully show the great potential benefits of this technology, which will then drive further research into reducing the costs of the wire.

A critical component for this future research is a large variety of materials characterization tools. Within this large family the STM and the MFM hold a special place because they can probe some of the most fundamental superconducting properties directly, and with resolution down to the atomic scale. Such advanced technologies may indeed make possible the dream of finding new superconductors that can operate at room temperature [30].

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15. See, for example, *http://www.uh.edu/research/tcsuh/research/levitate.html.*
16. Reported by the Yamanashi Test Line on April 14, 1999. See *http://www.rtri.or.jp.*
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