Commercialization of Bi-2223 Superconducting Wires and Their Applications

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Sumitomo Electric Industries, Ltd. has been engaged in the development of high-performance and long-length Bi2223 high-temperature superconducting wires. These wires and their applied products, such as current leads for magnetic resonance imaging, have been commercialized and well received by the market. This paper describes the recent development and commercialization of Bi2223 wires and typical products incorporating the wires, as well as wire joint technology and high-current conductor technology, which are indispensable for expanding the application of the wires.

1. Introduction

It has been more than 30 years since the high-temperature superconductor was discovered in 1986. At Sumitomo Electric Industries, Ltd., we started to work on applying this substance to wires and developing applied products immediately after the discovery of the high-temperature superconductor because a major breakthrough was likely to occur in the energy transmission field.

Today, only the rare earth-based (REBCO, rare earth-Ba-Cu-O) and bismuth-based (Bi-Sr-Ca-Cu-O-based) materials are industrialized and commercialized as practical materials. Wires and applied products using wires have been mostly developed from these two types of materials. The bismuth-based high-temperature superconducting wires are classified into two main categories based on the composition ratio: Bi-2212 wires (critical temperature, about 90 K) and Bi-2223 wires (critical temperature, about 110 K). The Bi-2212 wires can be applied only to high magnetic fields at 4.2 K; therefore, the Bi-2223 wires and applied devices have been developed because they can be applied in the wide temperature range (from 4.2 K (liquid helium temperature) to 77.3 K (liquid nitrogen temperature)).

We started to commercialize the Bi-2223 wires under the product name of DI-BSCCO wires. In line with the launch of the products, we worked to develop applied products and create new businesses. In the course of DI-BSCCO wire commercialization, we endeavored to expand the product lineup (e.g., high-strength wires) and develop peripheral technologies for wires (e.g., development of splicing technologies and large-current conductors) to meet the requirements from application sides.

In terms of the development of applied products, we supplied final products, intermediate products (e.g., coils), and wires according to the cooperation with customers.

This paper presents the current status of the commercialization and development of the DI-BSCCO wires and development examples of applied products using the DI-BSCCO wires.

2. Bismuth-Based High-Temperature Superconducting Wires

2-1 DI-BSCCO wire products

Our DI-BSCCO wires are manufactured based on the powder-in-tube method using Ag sheaths. They have a multicore structure, with many Bi-2223 thin wire filaments in the Ag matrix.

Photo 1 shows the cross section of a wire. Applying controlled overpressure sintering method achieved superconducting filaments with almost 100% density. Increased density of filaments has made it possible to improve the strength and reduce defects, in particular.[1]–[3]

Photo 1. Cross section of a DI-BSCCO wire

We have added various types of products based on these basic wire manufacturing processes. The lineup of wires that we have commercialized is shown in Table 1.

2-2 Ag-Au sheath wires

Ag is characterized by the highest thermal conductivity in the metallic materials. High-temperature superconductors, which can maintain the superconductive state up to high temperature, are expected to be used as current leads for energization of magnets. To achieve ideal current leads, it is necessary to attain zero resistance up to high temperature and reduce heat penetration attributed to thermal conduction.

To reduce the thermal conduction of Ag, we selected an Ag-Au alloy sheath that can reduce thermal conduction without deterioration of the superconducting characteristics. The thermal conductivity can be lowered by increasing the Au concentration. However, the Ag-5.4 wt% Au alloy was selected by taking into account the balance with the cost. The rest of the structure is equivalent to that of the standard high current-density type wires.

Figure 1 shows the temperature dependency of

Table 1. Specifications of the DI-BSCCO wires

	Type H	Type G	Type HT-SS	Type HT-CA	Type HT-NX
	High current density wire	Low thermal conductivity wire	High mechanical strength wire with different reinforcement material		
Typical Application		Current Lead	Magnet	Power cable	High field magnet
Average Width	4.2+/- 0.2 mm	4.2+/- 0.2 mm	4.5+/- 0.1 mm	4.5+/- 0.1 mm	4.5+/- 0.2 mm
Average Thickness	0.23+/- 0.01 mm	0.23+/- 0.01 mm	0.29+/- 0.02 mm	0.35+/- 0.02 mm	0.31+/- 0.03 mm
Matrix	Ag alloy	Ag-Au 5.4wt%	Ag alloy	Ag alloy	Ag alloy
Reinforcement tape Thickness	–	–	Stainless steel (0.02 mm^t)	Copper alloy (0.05 mm^t)	Nickel alloy (0.03 mm^t)
Critical Current, Ic *[1] 77K, Self Field	170 A, 180 A, 190 A, 200 A				
Wire Tension * RT, 95% Ic retention	80 N *	80 N *	230 N *	280 N *	410 N *
Tensile Strength * 77K, 95% Ic retention	130 MPa *	130 MPa *	270 MPa *	250 MPa *	400 MPa *
Tensile Strain * 77K, 95% Ic retention	0.2% *	0.2% *	0.4% *	0.3% *	0.5% *
Double Bending Diameter * RT, 95% Ic retention	80 mm *	80 mm *	60 mm *	60 mm *	40 mm *

* Typical value

thermal conductivity of these wires.[4] It shows a nearly 2 orders of magnitude decrease in thermal conductivity in the temperature range of 10–20 K.
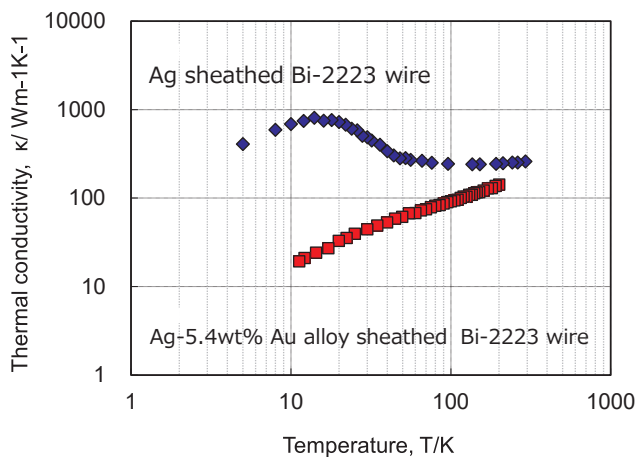

Fig. 1. Thermal conductivity of the wire

2-3 High-strength wires

In the case of the Type H wires (standard high-current-density type wires), the tensile stress at which the critical current (Ic)*[1] does not deteriorate is 130 MPa at 77.3 K. When the electromagnetic force is high (e.g., large diameter and high field magnets), the characteristics mechanically deteriorate. For this reason, it was necessary to increase the strength of the wires. We developed a technology to laminate the reinforcement on both sides of a Type H wire using solder. Bi-based superconductors are a type of ceramics and therefore are susceptible to tensile stress. To improve the critical tensile stress characteristics of wires, it is effective to apply compressive residual stress

to the superconductor.

We were able to control the compressive residual stress and improve the critical tensile stress characteristics by selecting the appropriate reinforcement material and thickness and applying tensile force to the reinforcement during lamination. The critical tensile stress characteristics of the wires that have been commercialized are shown in Fig. 2. In the case of the Type HT-SS (which uses stainless steel for reinforcement) and the Type HT-CA (which uses Cu alloy for reinforcement), the Ic does not decrease to about 250 MPa at 77.3 K.

The Type HT-SS is mainly applied to magnets, and the Type HT-CA is widely used for power cables in particular due to its low electrical resistance. In the applications for the high field magnets at more than 20 T, the critical tensile stress of 250 MPa is still inadequate. Thus, we developed the Type HT-NX using a special Ni alloy, which made it possible to withstand the tensile stress of up to 400 MPa. It has been found that the critical tensile strain characteristics is improved in line with the improvement of the tensile
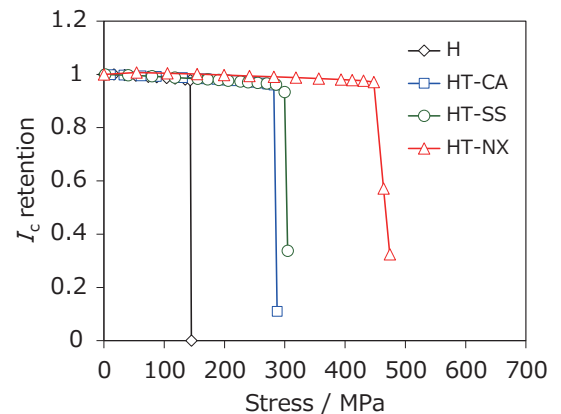

Fig. 2. Tensile stress dependency of the wire Ic

stress characteristics (refer to Table 1).[5]

As discussed below, the Type HT-NX wires led to the realization of magnets at the 25 T level. It should be noted that using a special Ni alloy resulted in high costs. With the onset of projects to develop 30–40 T-class magnets in the world, there were growing demands for high-strength wires surpassing the Type HT-NX. To meet such needs, we developed a low-cost 400 MPa-class wire using 0.08 mmt stainless steel for reinforcement. Regarding the 500 MPa-class wires, we developed a wire using Ni alloy of 0.1 mm^t (Fig. 3).

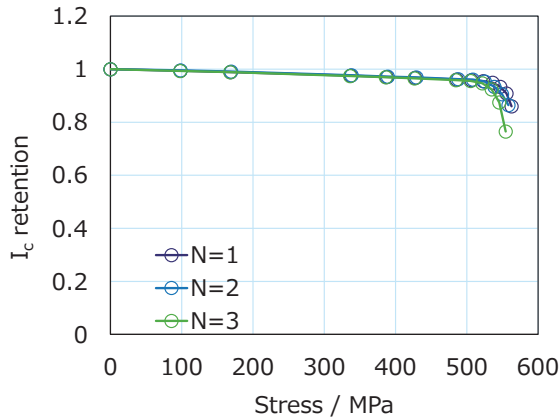Fig. 4. Lap length dependency of solder splicing resistance

Fig. 3. Tensile stress characteristics of a 500 MPa-class high-strength wire

3. Splicing Technology

Given the costs to manufacture wires and application devices, it is essential to use short-length wires properly. Even if it is possible to manufacture long-length wires, splicing cannot be avoided for application of magnets and cables. Thus, the splicing technology is very important in developing applied products and expanding the applications.

3-1 Low-resistance splicing

The matrix of the Type H wires is made of a low-concentration Ag alloy. This enables low-resistance splicing compared to soldering of low-resistance metals, such as Cu. This is because the splicing resistance depends on the electrical resistance of the wires, solder, and matrix among other factors. In the case of the Type HT-based wires that have reinforcement on their surface, the electrical resistance of the reinforcement and the splicing area have a significant impact on the splicing resistance.

Figure 4 shows the overlapping length dependency of the splicing resistance when the wire surfaces (reinforcement surfaces) are spliced by soldering.[5] The longer the overlapping length, the lower the splicing resistance. However, the bending characteristics deteriorate. Thus, it is necessary to select an optimal overlapping length depending on the application. For the Type HT-CA wires for cables, the standard overlapping length is 20 mm. The Type HT-NX wires are effective for high field magnets, but the regular solder splicing results in high splicing resistance.
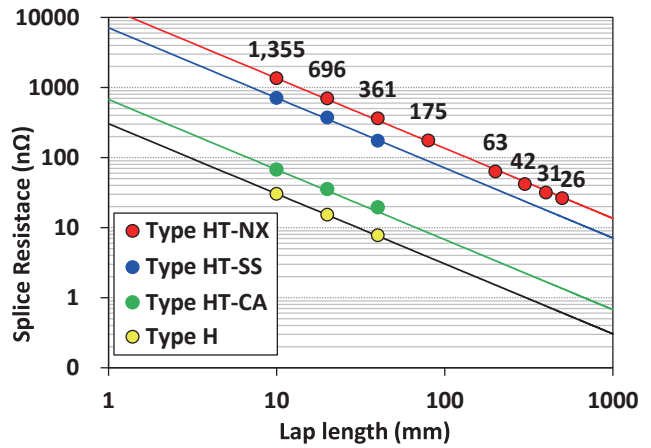
Low splicing resistance can be achieved by peeling off the reinforcement for splicing of the Ag sheaths. However, peeling off releases the residual compressive stress, resulting in failure to maintain the mechanical strength. To achieve low splicing resistance while minimizing the decrease in mechanical strength, the reinforcement was partially peeled off and a Cu tape was arranged in the clearance, making it possible to achieve both low splicing resistance and high strength. The schematic diagram of a splicing is shown in Fig. 5. For example, splicing resistance of 54 nΩ was attained at 77.3 K by setting the overlapping length to 40 mm, peeling off the reinforcement by 20 mm, and inserting an 18 mm Cu tape. Regarding the critical tensile stress characteristics, 416 MPa was attained based on the same splicing structure using 423 MPa wires without splicing, achieving the strength retention rate of 98%.[5]
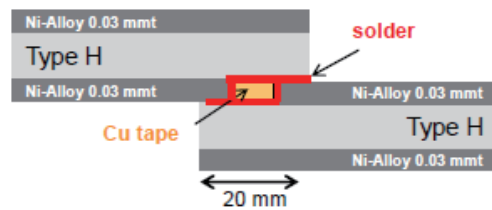
Fig. 5. High-strength & low-resistance structure of a solder spliced Type HT-NX wire

3-2 Superconducting joint

For magnets that are required to attain a highly stable magnetic field in the order of ppm to ppb per unit time, as in the case of magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR), it is difficult to attain the required stability due to the fluctuation of the current output, unless a special DC power source is used.

Conventional high-stability magnets using low-temperature superconducting wires are operated separately from the power source based on the persistent current operation. To achieve persistent current operation, the splicing

must be superconductive, and the splicing resistance required for each design must be attained because the decay time constant of the persistent current is determined by the ratio between the magnet inductance and resistance.

Regarding the superconducting joint technology for the DI-BSCCO wires, superconducting joint of a practical level can be achieved by polishing two wires at a low angle (1° or less) in advance and performing heat treatment with a Bi-2223 thick film sandwiched. Such low-angle polishing allows all the multicore filaments to contribute to the joint. Figure 6 shows the schematic diagram of the joint, and Fig. 7 shows the critical current characteristics of the superconducting joint.[6]
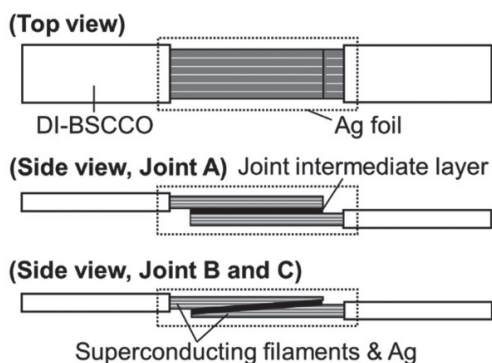

Fig. 6. Structure of the superconducting joint[6]
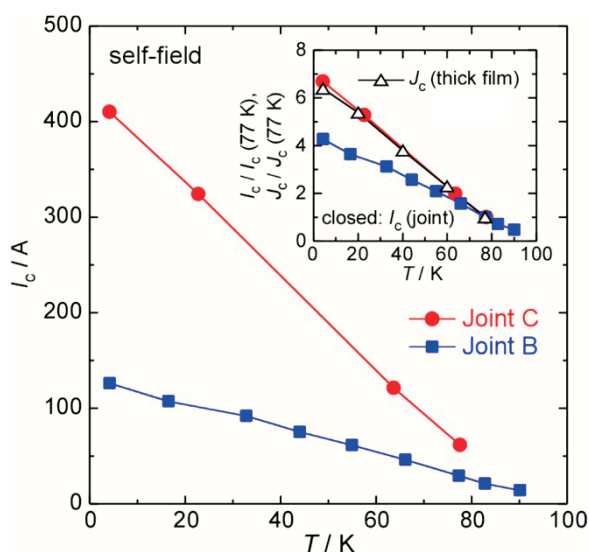

Fig. 7. Ic characteristics of the superconducting joint[6]

At Joint A, the Ic is low because the number of exposed filaments is low. The joint resistance was also measured at the superconducting joint with the low-angle polishing. It was $< 10^{-13}$ Ω under the conditions of 4.2 K and 1 T with the NMR applications taken into account.[7]

In the high field applications at 4.2 K, a high Ic can be attained even if the joint part turns into the Bi-2212 phase.

It should be noted that the Bi-2212 phase appears from the Bi-2223 phase due to the semi-molten state. A superconducting joint method that utilizes such phase transformation has also been developed.[8]

4. Large-Current Conductors

The maximum Ic of DI-BSCCO wire at 77.3 K, self-magnetic field is 200 A. To achieve large-current and low-inductance magnets for nuclear fusion and accelerator, it is necessary to bundle multiple wires and fabricate large-current conductors.

Previously, methods to stack multiple wires were tested. However, the current distribution is likely to be uneven in such methods when the current is changed (e.g., during magnet excitation).

A technology for creating a transposed conductor by changing the position of the DI-BSCCO wires (which are tape wires) was developed using the Type HT-NX wires. Solid Material Solutions, LLC started to commercialize the conductor under the product name of Magnum-NX.[9] The configuration and appearance of the conductor are shown in Fig. 8.[10]
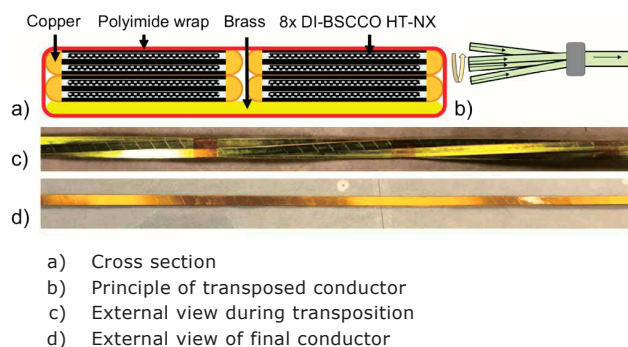

a) Cross section
b) Principle of transposed conductor
c) External view during transposition
d) External view of final conductor

Fig. 8. Large-current transposed conductor[10]

5. Development of Applied products

Various applied products were developed in line with the development of the DI-BSCCO wires, leading to the creation of applied products at the practical level. There are two main application fields: magnets and energy transmission (e.g., power cables, current leads).

5-1 Application to magnets

The application of the DI-BSCCO wires to magnets in the medium magnetic field application (several T to more than 10 T) has enabled operation at around 20 K, at which low-temperature superconducting magnets made by NbTi or other materials cannot be operated. High magnetic fields exceeding 20 T can be generated in the 4.2 K range.

(1) Conduction cooled magnets

Operation of magnets in the 20 K range, in which low-temperature superconducting magnets cannot be operated, offers a solution for the recent He supply shortage.

The temperature of 20 K is only about 15 K higher than 4.2 K of the liquid He. However, the specific heat is about 100 times greater than that at 4.2 K He. The temperature increase is small even if there is thermal disturbance, and the critical temperature is high. Thus, the temperature margin of transition from the superconducting state to the normal conducting state is large. In a variable magnetic field, superconductors generate heat due to the AC loss, but stable operation is possible.

In the 20 K cooling, conduction cooling becomes possible using a refrigerator for cryopumps (a type of vacuum pump). The temperature required for operation can be easily attained by turning on the power source switch.

A high-temperature superconducting magnet is likely to prevent propagation of the normal zone once a seed of the normal conducting state occurs because the conductor is made from low thermal conductive oxide ceramics. Burnout may result due to local heating. It should be noted that the normal zone propagation is relatively fast compared to other high-temperature superconducting wires because the DI-BSCCO wires have an Ag sheath. Thus, detection of the normal conducting state and protection can be achieved in a method similar to that of low-temperature superconducting magnets.[11]

Photo 2 shows the examples of solenoid type conduction cooled magnets. The 6 T magnet (bore at room temperature, 70 mm) was commercialized by building it into the apparatus for measuring the magnetization curve of high-performance rare earth permanent magnets. Quick excitation (30 seconds up to 6 T) is possible.

Photo 2. 20 K conduction cooled magnet

Regarding the Helmholtz type split magnets, a hard disk inspection magnet (Photo 3) was developed.

Other examples of 20 K conduction cooled magnets include the MRI 3 T magnets for the brain,[12],[13] 1.5 T magnets for the limbs (conduction cooled by closed loop circulation of the 27 K liquid neon),[14] and 1.5 T magnets for newborn.[15] MRI systems for special applications (instead of whole body types) have been developed.

Varian Medical Systems, Inc. has been working to develop accelerator applications for the medical proton cyclotrons. Specifically, the abovementioned Magnum-NX is used for the main coil of cyclotrons, and the DI-BSCCO wires are used for the flutter coils to correct the proton

Photo 3. Magnet for hard disk inspection
(Courtesy of NEOARK CORPORATION)

beam orbit.[10]

Meanwhile, Osaka University has been studying the possibility of applying DI-BSCCO wires to various types of magnets for accelerators.[16]

(2) High field magnets

One of the examples of the high field magnets using the Type HT-NX is the 25 T magnet, which is available as user magnet at the Institute for Materials Research, Tohoku University. The magnet consists of a low-temperature superconducting coil on the outside and a Type HT-NX-based high-temperature superconducting coil on the inside. This is a 4 K conduction cooled type. It has been operated for more than three years (more than 200 days per year) for many experiments including the solid NMR.[17]

For the high field NMR, a Japanese national project is underway to develop a magnet that can be operated in the persistent current mode at the proton resonance frequency of 1.3 GHz (30.5 T). At this moment, the Type HT-NX was used for part of the magnet to successfully produce 30 T at 4.2 K.[18] The persistent current operation has not started yet, but the project aims to realize an NMR system that can perform persistent current operation by utilizing the abovementioned superconducting joint technology.[19]

5-2 Current leads

While the conventional copper current leads are characterized by the theoretical maximum heat penetration amount of 1 W/kA, the Type G wires for the current lead applications can reduce the heat penetration amount to the 0.2 W/kA level. These wires have been widely used for liquid helium cooling magnets, including commercial MRI magnets, making significant contributions to reducing the liquid helium evaporation amount.

In the International Thermonuclear Experimental Reactor (ITER) project, a current lead using the Type G wires (maximum current capacity, 68 kA) was developed by the Institute of Plasma Physics, Chinese Academy of Sciences. A current lead for the ITER system was fabricated.[20]

To achieve a conduction cooled magnet at 20 K or 4.2 K, it is indispensable to use a high-temperature superconducting current lead due to the restrictions of the cooling capacity. Such current lead is used for various magnets mentioned above.

5-3 Superconducting power cables

Various projects are underway around the world to develop superconducting cables to reduce the loss of the power transmission and distribution cables, reduce the size to increase the capacity using the existing ducts by replacing the conventional normal conducting cables, and reduce the installation space, in particular. There were ideas for superconducting cables before the discovery of the high-temperature superconductors. However, it was difficult to achieve long-distance cooling using liquid helium. The development of high-temperature superconducting cables, which use liquid nitrogen as a refrigerant, opened up the possibility of practical application.

Examples of cable projects using the DI-BSCCO wires include the Albany project in the U.S.,[21] Yokohama project in Japan,[22] AmpaCity project in Germany,[23] and DC cable project in Saint Petersburg, Russia.[24] In addition to the applications to power transmission, the possibility of applying superconducting cables to railway feeder system has been studied.[25]

The Type HT-CA wires are used in most of these projects. One of the reason is the Type HT-CA wires are characterized by high mechanical strength. In addition, power cables are unlikely to deteriorate even if a large accident current exceeding the critical current (e.g., short circuit current) flows. Therefore, another reason is reinforcement is low resistance and low heat generation if large accident current flows. A low splicing resistance between cables can be achieved by solder splicing. Figure 9 shows a 66 kV cable that we developed.
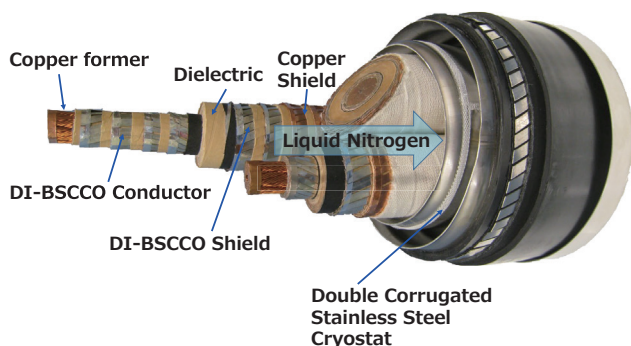

Fig. 9. Three-in-one cable

6. Conclusion

This paper introduced the progress in the commercialization of the DI-BSCCO wires and the development status of various applied products using the DI-BSCCO wires. Recently, these wires have been used for practical products such as current leads. It should be noted that practical applications have just begun. We will continue to expand the application fields and the scope of the commercialization in full scale.

Technical Term

*1 Critical current Ic: The largest current that can flow with zero electrical resistance.

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