Semiconductor Sensors:

Ch3: Electromagnetic Sensors cont.

Lecturer: Dr. Navid Alaei Sheini
Shahid Chamran University of Ahvaz

ابر رسانایی:

Superconductivity was discovered in 1911 by H. Kamerlingh Onnes in Holland during study of the electrical resistance of frozen mercury as a function of temperature. When cooling Hg to the temperature of liquid helium, he found that the resistance vanished abruptly at approximately 4 K (= −269.15°C). Onnes was the first to liquify helium in 1908. In 1913 he won the Nobel Prize for his liquification of helium and discovery of superconductivity.

ابر رساناهای دما بالا و دما پایین:

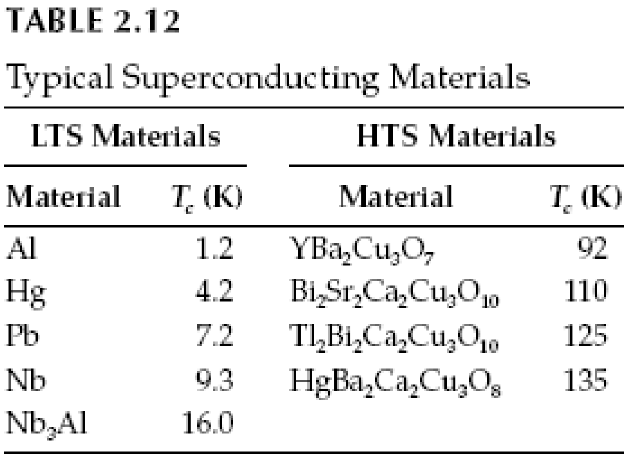


TABLE 2.12

Typical Superconducting Materials

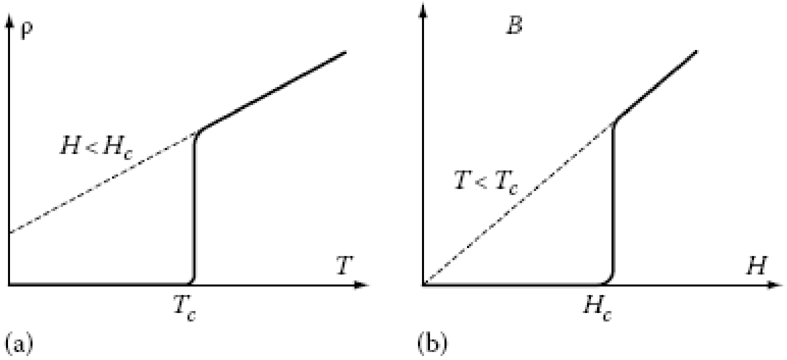
LTS Materials		HTS Materials	
Material	**T_c (K)**	**Material**	**T_c (K)**
Al	1.2	$YBa_2Cu_3O_7$	92
Hg	4.2	$Bi_2Sr_2Ca_2Cu_3O_{10}$	110
Pb	7.2	$Tl_2Bi_2Ca_2Cu_3O_{10}$	125
Nb	9.3	$HgBa_2Ca_2Cu_3O_8$	135
Nb_3Al	16.0		

W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

ابر رسانایی:

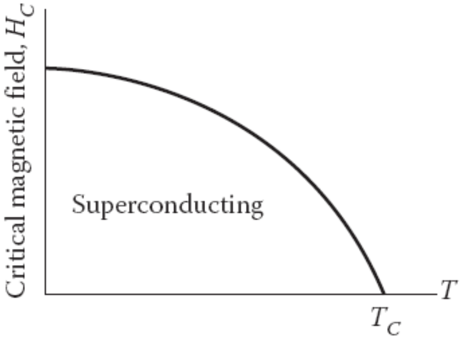
دو خاصیت اصلی ابر رسانا: ۱- مقاومت الکتریکی صفر (R=0)؛ ۲- دیامغناطیس کامل (μ=0)

- **دمای بحرانی**
- **شدت میدان مغناطیسی بحرانی**
- **وابستگی دمایی شدت میدان مغناطیسی بحرانی**
- **جریان بحرانی**



(a) (b)

FIGURE 2.60
The material becomes a perfect conductor (a) and perfect diamagnetic (b) at low temperature.



Temperature dependence of the critical field H_C.

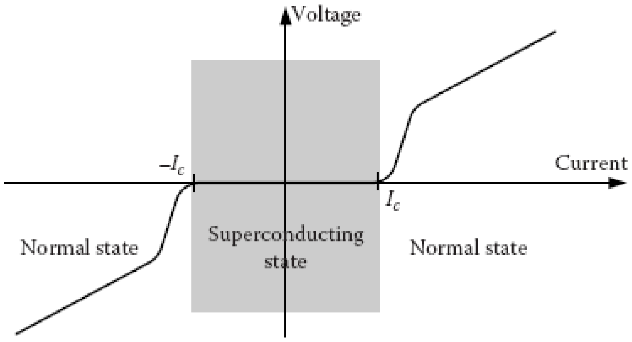
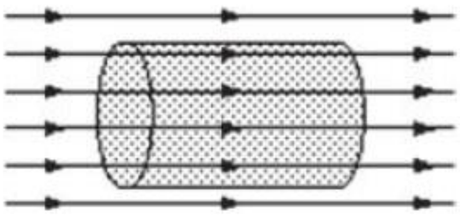


FIGURE 4.159
Voltage versus current of a shunted Josephson junction.

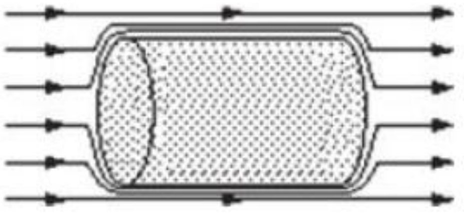
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 38.

Meissner Effect ابر رسانایی:

The *Meissner–Ochsenfeld effect*, discovered in 1933, states that magnetic fields are expelled from superconducting materials when the materials are cooled below their *critical* or *transition* temperature, *T*c. This feature differs from that of normal conducting materials in which magnetic flux lines can penetrate through the material.



Normal conducting ($T > T_c$)



Superconducting
Meissner effect ($T < T_c$)

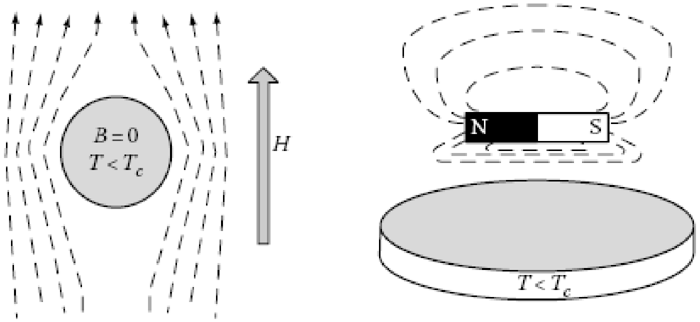
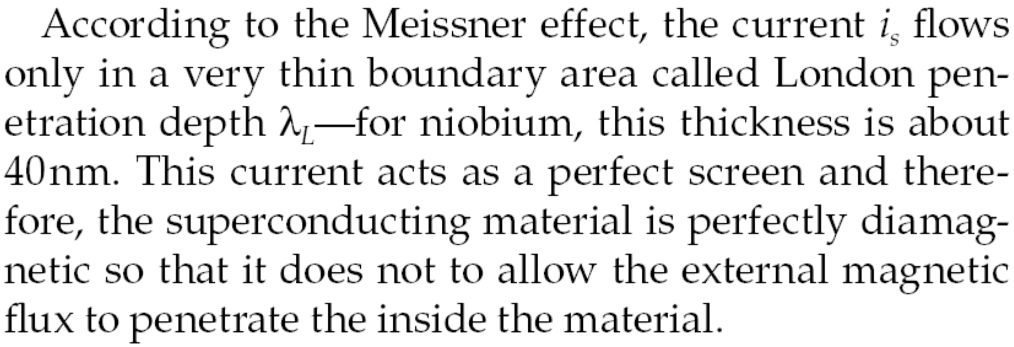


FIGURE 2.61
Two experiments illustrating the Meissner effect.

screening current, i_S



According to the Meissner effect, the current i_s flows only in a very thin boundary area called London penetration depth λ_L—for niobium, this thickness is about 40nm. This current acts as a perfect screen and therefore, the superconducting material is perfectly diamagnetic so that it does not to allow the external magnetic flux to penetrate the inside the material.

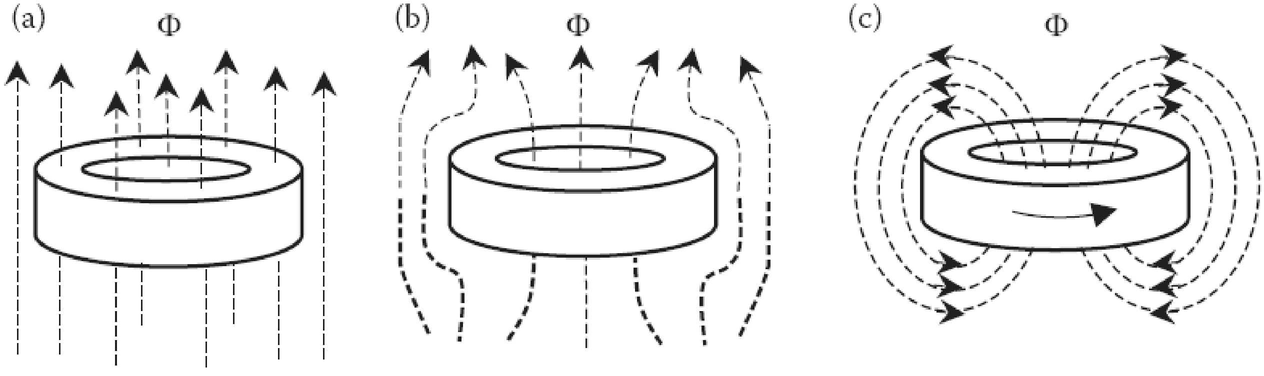
W. Y. Du ”*Resistive, capacitive, inductive, and magnetic sensor technologies*”, CRC Press, 2014.
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

ابر رسانایی:

For a conductor ring If the magnetic field is removed or turned off, an eddy current is induced and circulates around the ring, trapping or keeping the magnetic flux inside (constant). The induced current will decay exponentially with a time constant that relates to the resistance *R* and inductance *L* by

$$I(t) = I_0 e^{-(R/L)t}$$

When the temperature is below, the ring is in the superconducting state (*R* = 0), and the magnetic flux is expelled from the ring, but the flux, Φ, through the ring's opening remains unchanged. If the external field is switched OFF, the induced eddy current appears and never decays. This persistent, constant, circulating current creates a constant magnetic field around the ring.



Normal ($T > T_c$)
(non-superconducting)

Meissner effect ($T < T_c$)
magnetic field ON
(superconducting)

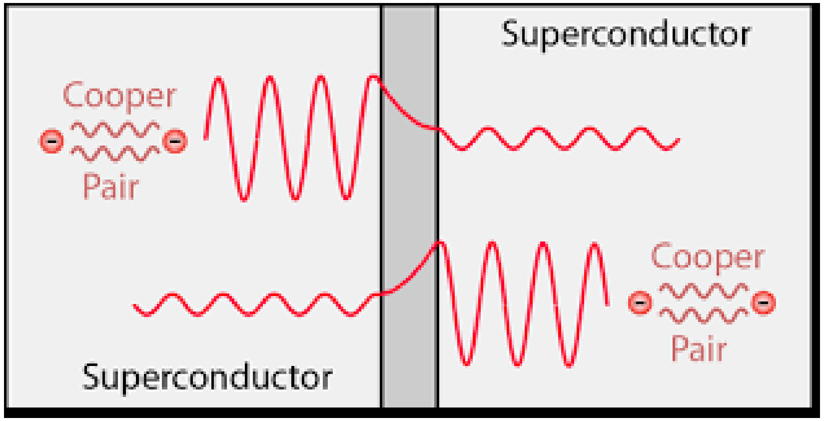
Meissner effect ($T < T_c$)
magnetic field OFF

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

ابر رسانایی:

What is cooper pairs? What causes by cooper paris?

The resistance of almost all conductors decreases with decrease of the temperature due to reduced scattering of free electrons. But the superconductivity is related to other mechanism. Conducting occurs due to pairs of electrons with opposite moments and spins—*Copper pairs*. The Cooper pair comprises two mutually bound electrons existing only at low temperature. The phenomenon of conduction at low temperature by a Cooper pair results in various extraordinary quantum effects: conduction through a thin insulator barrier (*tunneling effect* or *Josephson effect*), magnetic flux quantization, quantumHall effect, etc. These effects are very important also in magnetic measurements.

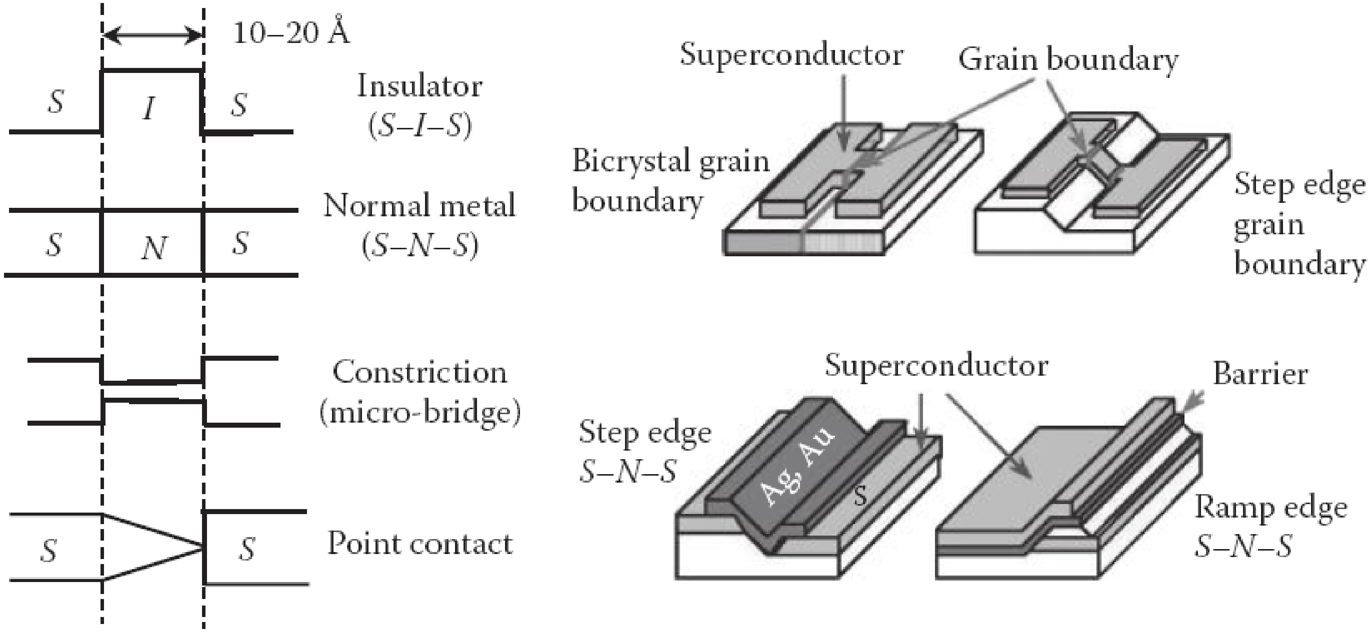


S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)- page 38.

اتصال دو ابر رسانا:

Josephson Effect

Josephson effect, named after the British physicist—Brian D. Josephson who predicted the effect in 1962 and won the Nobel Prize in physics in 1973, is a prediction of current flowing across two weakly linked superconductors. The weak link, called *Josephson junction*, can be a thin insulating layer (known as a superconductor–insulator–superconductor junction, or *S*–*I*–*S*), a short section of non-superconducting metal (*S*–*N*–*S*), a physical constriction (e.g., a micro-bridge), or a point of contact (*S*-*s*-*S*). The first Josephson junction was made by John Anderson at *Bell Labs* in 1963.



W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

اتصال دو ابر رسانا:

Josephson junction current equations:

The current in the junction is described by two following equations:

$$i_s = I_c \sin\theta \qquad (2.85)$$

$$f = \frac{d\theta}{dt} = \frac{2e}{h}V \qquad (2.86)$$

The first Josephson Equation 2.85 describes the DC current *is* in the junction. The current *Ic* is a parameter of the junction and it is the *critical current*—if current exceeds this value, the superconducting effect vanishes. The angle θ (*an order parameter*) is the phase difference between wave functions of electrons in pair at both sides of the junction.

EXAMPLE 5.20

The phase difference of two superconductors on both sides of a Josephson junction is 8°. If the critical current and the temperature of the material (same for both superconductors) is 0.2 mA and 7.16 K, respectively, find the current flows through the junction.

$$i_s = I_c \sin\theta = (0.2\ \text{mA})\sin 8^\circ = 0.0278\ \text{mA}$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

اتصال دو ابر رسانا:

Josephson junction AC current equation:

$$f = \frac{d\theta}{dt} = \frac{2e}{h} V \qquad (2.86)$$

The second Josephson Equation 2.86 describes the frequency of alternating current when we supply the junction by DC voltage *V*.

If we put the Josephson junction in a high-frequency magnetic field, we obtain the quantum standard of voltage. In this standard, voltage versus current changes stepwise (is quantized) with the step value:

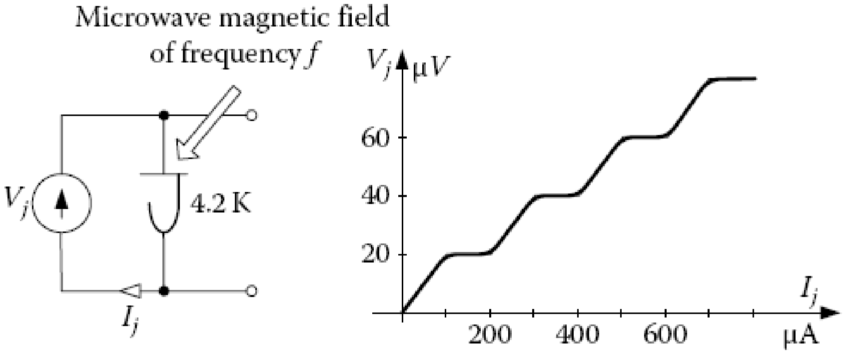


FIGURE 2.64
The Josephson junction as a voltage standard.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.
S. Tumanski-Handbook of Magnetic Measurements -CRC (2011)

حسگرهای مغناطیسی SQUID:

AC Josephson Effect:

If the Josephson current exceeds the Josephson junction's critical current I_C ,the Josephson voltage appears across the junction. The *AC Josephson equation* relates the voltage across the junction, $V_{J(t)}$, to the temporal derivative of δ as

$$V_J(t) = \frac{K_P}{2q}\frac{\partial\delta}{\partial t}$$

where K_P is *Plank's constant* (6.626176×10^{-34} J · s); q is the charge of an electron. An AC current should flow across the junction under $V_J(t)$. Josephson also predicted that the I–V curve of the junction should show spikes at intervals of $q\omega/K_P$, where ω is the frequency of the AC current. The constant, $\Phi_0 = K_P/(2q) = 2.06783367 \times 10^{-15}$ Wb (or T · m^2), is the *magnetic flux quantum*. Its inverse is the *Josephson constant*, $K_J = 1/\Phi_0 = 2q/K_P = 483597.89 \times 10^9$ Hz · V^{-1}.

EXAMPLE 5.21

Find the phase change rate when the voltage across the Josephson junction is 2 mV.

$$\frac{\partial\delta}{\partial t} = \frac{2q}{K_P}V_J(t) = \frac{2\,(1.602 \times 10^{-19}\text{C})(2 \times 10^{-3}\text{ V})}{6.626176 \times 10^{-34}\text{ J} \cdot \text{s}} = 967\text{ GHz}$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES حسگرهای مغناطیسی SQUIDs:

SQUID joins two effects: quantization of magnetic flux and tunneling by a weak link (Josephson effect).

SQUID is a superconducting ring sample with one or two Josephson tunneling junctions:

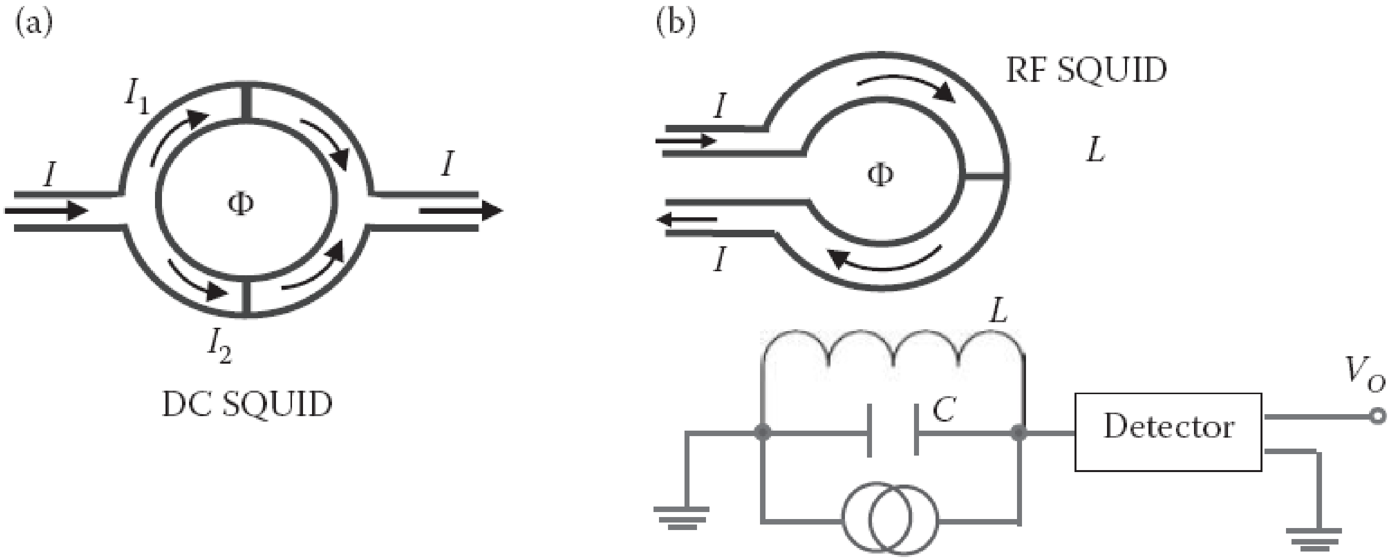
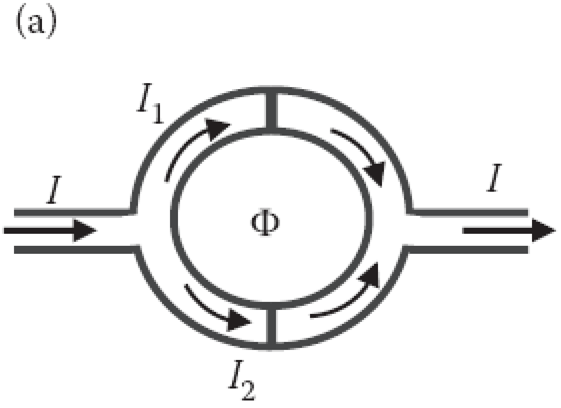


FIGURE 5.63 Two types of SQUIDs: (a) DC SQUID; (b) RF SQUID.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

DC-SQUIDs:

حسگرهای مغناطیسی SQUIDs:



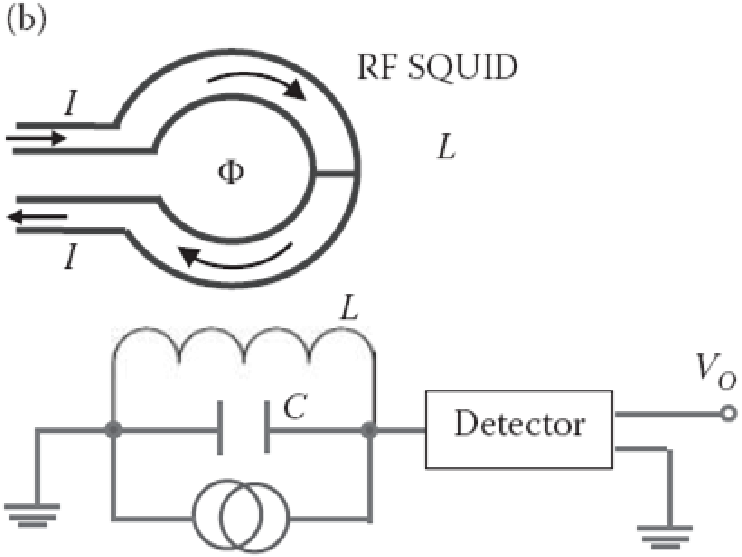
DC SQUID

A DC SQUID is based on DC Josephson effect. It has a superconducting loop interrupted by two Josephson junctions. In the absence of an external magnetic field, the input current, I, splits into the two branches equally. If a small external magnetic field is applied to the superconducting loop, an induced current (called *screening current*, I_S) begins circulating in the loop and generates a magnetic field against the applied external flux. Thus, I_S is in the same direction as I in one of the branches of the superconducting loop, and is opposite to I in the other branch. The total current, therefore, becomes $I/2 + I_S$ in one branch and $I/2 - I_S$ in the other. As soon as the current in either branch exceeds the junction's critical current, the Josephson voltage appears across the junction.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

RF-SQUIDs:

حسگرهای مغناطیسی SQUIDs:



An RF SQUID is based on the AC Josephson effect and has only one Josephson junction. The RF SQUID is inductively coupled to a resonant tank or *LC*. When an external magnetic field is applied, the conductivity of SQUID alters, causing a change in the effective inductance and thus the resonant frequency of the *LC* circuit. The variation in the resonant frequency can be easily measured and converted to an output voltage that is proportional to the strength and frequency of the applied magnetic field.

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.