

# Chapter 2. Superconducting Electronic Devices

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## 2.1 High $T_c$ Superconducting SQUIDs and Mixers

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Many superconducting analog devices have been demonstrated to have higher sensitivities, speed, and frequency limits and lower power dissipation than competing semiconductor devices. Among the superconducting devices, the most successful ones are SQUIDs (Superconducting QUantum Interference Devices) and mixers.

Similar to its optical analog, the Mach-Zehnder interferometer, a SQUID is an interferometer composed of two waves of superconducting electrons. By modulating the relative phases of the two waves using a small magnetic field, a SQUID magnetometer can achieve the sensitivity of a fraction of magnetic quantum flux. Superconducting mixers use the high nonlinearity of the current-voltage characteristics of superconducting tunnel junctions to perform high-efficiency mixing. Currently, superconducting mixers have the highest sensitivities which are only limited by Heisenberg's uncertainty principle.

The discovery of superconductors with a superconducting transition temperature higher than liquid nitrogen temperature (high- $T_c$  superconductors) has opened up exciting new possibilities in electronic device technology. The high temperature version of the superconducting devices mentioned above will have a much wider range of applications wherever refrigeration is a problem. However, the benefit of higher operating temperature has posed a new challenge which is not encountered in conventional superconducting devices. The key element for both SQUIDs and

mixers is the so-called Josephson junction. This junction is formed by two superconductors weakly coupled together electrically. Heisenberg's uncertainty principle dictates that higher transition temperature will result in a shorter superconducting coherence length. This is the length scale at which superconductivity vanishes at an interfacial boundary. Consequently, high- $T_c$  Josephson junctions require that the weaklink regions are much smaller than those for low  $T_c$  devices.

In collaboration with Dr. Melngailis' group, we have invented several novel ways of making high  $T_c$  superconducting devices using focused ion beams (FIB). FIBs can be used to either lithographically pattern high- $T_c$  superconducting films or to directly pattern the films or the substrates to form Josephson junctions. Currently, we are optimizing our process to improve the quality of the Josephson junctions.

This work is being performed with the cooperation of the AT&T Bell Laboratories in Murray Hills, New Jersey.

## 2.2 Millimeter Wave and Infrared Superconducting Receivers

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Although there is great potential for applications in remote sensing and communication, millimeter wave and far-infrared frequencies remain one of the most underdeveloped frequency ranges. This is because the millimeter wave and far-infrared frequency range falls between the two other frequency ranges in which conventional

semiconductor devices are usually operated. One is the microwave frequency range, and the other is the near-infrared and optical frequency range. Semiconductor devices which utilize the classical diffusive transport of electrons, such as diodes and transistors, have a high frequency limit. This limit is set by the time it takes for electrons to travel a certain distance. Currently, electron mobility and the smallest feature size which can be fabricated by lithography limit the frequency range to below 100 GHz. It is not likely that this limit can be pushed much higher. Semiconductor devices based on quantum mechanical interband transitions, however, are limited to frequencies higher than those corresponding to the semiconductor energy gap, which is higher than 10 THz for most bulk semiconductors. Therefore, a large gap exists from 100 GHz to 10 THz in which very few devices are available.

The gap energies of conventional superconductors such as Nb are in the range of 100 GHz to 2 THz. This coincidence makes superconducting devices natural candidates for millimeter and submillimeter wave applications. In addition, superconducting devices usually have higher sensitivities and speed and lower power dissipation than semiconductor devices. Two types of superconducting devices are studied in this project: coherent heterodyne

receivers and incoherent radiation detectors. The former has potential applications in communication as well as radiation detection, while the latter is usually used for remote sensing.

At millimeter wave frequencies, superconducting radiation detectors have their current responsivity approaching the quantum efficiency  $e/\hbar\omega$ , that is, a transport of one electron for one incoming photon. Such efficiencies have been achieved only at much higher frequencies by semiconductor photoconductive detectors. Therefore, superconducting radiation detectors may find wide-range applications in remote sensing and far-infrared spectroscopy.

At millimeter and submillimeter wavelengths, the superconducting coherent receivers have their sensitivities limited only by the zero-point fluctuation of vacuum. Such receivers have been used widely in astrophysical studies. More applications are feasible in space-based communication and far-infrared spectroscopy, which requires ultimate sensitivity.

This work is being performed with the cooperation of the MIT Lincoln Laboratory, IBM Corporation's Thomas J. Watson Research Center at Yorktown Heights, New York, and the AT&T Bell Laboratories in Murray Hills, New Jersey.