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Josephson Devices as Potential Circuit Elements in Ultra-Fast Computers

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Small switching times at very low power levels make Josephson junctions potential circuit elements for future high performance data processing systems. Both qualities are needed in high speed computers. Small switching times are a prerequisite, and the low power dissipation permits dense packing of circuits as well as utilization of terminated transmission lines.[1,2,3,4] This paper will review the properties of Josephson tunnel junction devices and circuits and present research results in computer applications.

A Josephson junction is a superconducting tunnel junction which, operating in liquid Helium, can be in either of two states. In the zero voltage state it behaves as a superconductor, carrying current without developing a voltage. If this current exceeds the Josephson threshold current or if a magnetic field is applied, the junction switches to the voltage state reaching a maximum potential given by the gap voltage of the materials used. For lead junctions the gap voltage is 2.5 mV.

For small junction dimensions, the transition between the zero-voltage and the voltage state occurs in tens of picoseconds.[5,6] Operating at low current and voltage levels, the device dissipation is extremely small (tens of μW).

The magnetic field required to switch the junction can be produced with overlayed control lines which are electrically insulated from the device. Each control line constitutes an input. Since the device switches only when the sum of the individual control fields reaches the threshold value it is possible to perform logic functions. Devices which switch with the field produced by a single control line are OR circuits, devices which require current in a number of lines perform the AND function, etc. Output currents are produced by connecting a terminated superconducting transmission line across the junction. The current produced in this line by the switched junction is fanned out serially to subsequent logic devices where it acts in turn as control current. Josephson tunnel juntions once switched remain latched in the voltage state. To revert them back into the zero-voltage state, the device current has to be momentarily reduced to a small value.

Experimental logic and memory circuits of varying complexity have been built and tested. These circuits were fabricated with lead alloy junctions using a process described by Greiner et al.[7] A one bit full adder[8] designed in a 50μm technology gave carry propagation in 200 ps and the "worst case" sum in 500 ps.

An experimental 4 bit multiplier[9] built with 45 Josephson gates in a 25μm technology was designed for a cycle time of 3.2 ns and was operated at an instrument limited cycle time of 6.67 ns. This led to a full multiplication of 4 x 4 bits in 27 ns. The dissipation was 35μW/gate.

Quantum interference Josephson logic devices have been explored. Containing more than one junction, these devices operate at still smaller voltage and current levels and can be designed to operate in a non-latching mode. Their characteristics are similar to that of a transistors. Non-latching circuits with a dissipation of <40 nW have been tested.[10]

Memory operation is based on the fact that quantized persistent currents can be stored in superconducting rings. The rings contain Josephson junctions and the direction of the stored current determines the state of the memory cell. This state can be altered by switching the junctions through coincidence of two currents. A junction which senses the stored magnetic flux allows non-destructive readout in bit organized arrays. Experimental memory cells have been built and tested.[11] Also, potentially small DRO memory cells which store single flux quanta have been experimentally explored.[12]

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