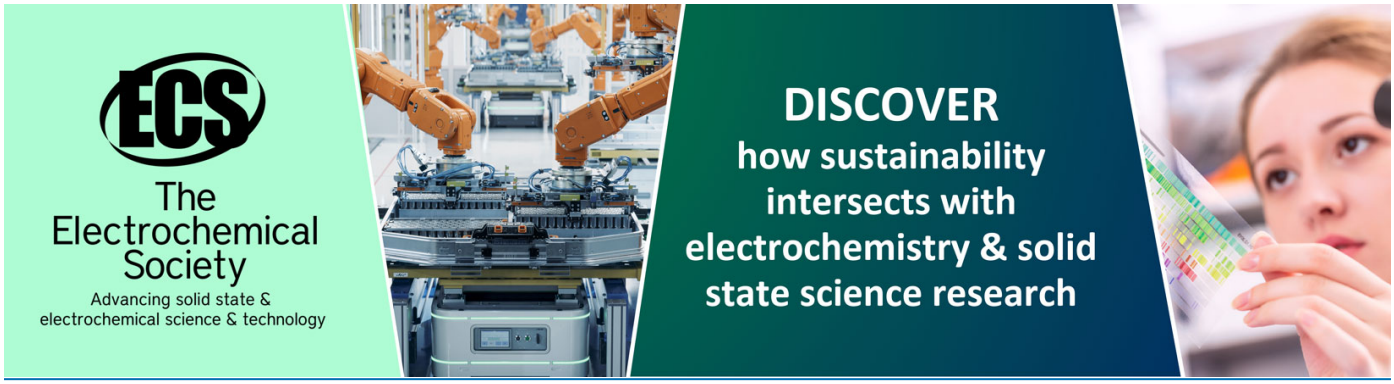
Sub-Kelvin single flux quantum control circuits and multi-chip packaging for supporting superconducting qubit



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Sub-Kelvin single flux quantum control circuits and multi-chip packaging for supporting superconducting qubit

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Abstract. Superconducting single flux quantum (SFQ) circuit can operate at very low temperature. This is suitable for controlling a quantum computing system with Josephson junctions. However, it is difficult to integrate both SFQ circuits and qubits into a single-chip, because of the dissipative characteristics of SFQ circuits. Therefore, we have developed a multi-chip packaging technology for a qubit control module. The module consists of SFQ circuit chips, qubit chips, and a substrate all of which are fabricated with Nb and Al technology. The chips are flip-chip bonded with superconducting solder bumps. We also investigated SFQ control circuits for superconducting qubits and circuit parameter optimization for sub-Kelvin temperature operation. Using both multi-chip packaging and optimized SFQ control circuit makes the design of qubit control module more flexible.

1. Introduction

Qubit operation requires precise control and readout techniques. Generally, external high-frequency signal sources have been used to control qubits. As increased with the number of qubits, many wide-band cables connecting between a room-temperature region and a dilution refrigerator are required. This is not practical. Superconducting single flux quantum (SFQ) circuit [1] has good compatibility with the Josephson junction qubit. Therefore, the SFQ circuit is a candidate for controlling multiple qubits. Using SFQ circuits makes possible the following advantages:

(a) high-speed control and high-sensitivity readout of the qubit states,
(b) flexible digital processing in the control circuit,
(c) shorter latency of control operations, because the control stage is located near the qubit without long interconnection, and
(d) sufficient integration scalability of SFQ circuits.

These are key advantages for achieving actual quantum computation with multiple qubits. In this work, we report our single flux quantum circuit design and packaging technology for qubit control.

2. SFQ-Qubit hybrid module technology

Figure 1 is a block diagram of an SFQ-controlled qubit. Incoming signals are first converted to SFQ pulses by the DC/SFQ circuits, and then processed in the controller circuit. Driver circuits convert the SFQ pulse output signals of the controller to suitable coupling signals. A tunable coupler handles the coupling between qubits. The tunable coupler is also used for coupling to the readout detection circuits, such as an SFQ analog-to-digital or time-to-digital converter. The detected information is fed back to the controller circuit.

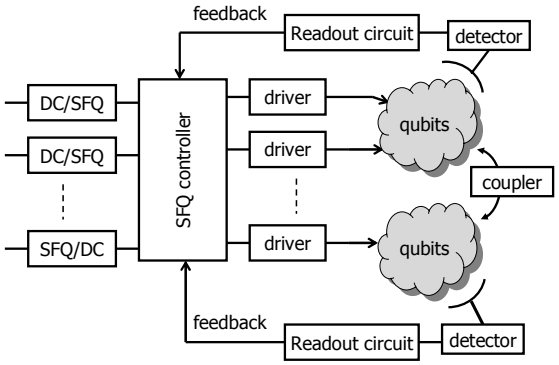

Figure 1. Block diagram of SFQ-controlled qubit

A main problem in implementing an SFQ supported multiple qubits system is its thermal budget. A multi-chip approach is a useful solution because the qubit chip can be isolated thermally from the SFQ circuitry. We have developed an SFQ circuit-qubit multi-chip module. The module consists of SFQ circuit chips, qubit chips, and a substrate. We can choose suitable device technology (in terms of fabrication, device parameters, etc.) for each chip, and this increases design flexibility. For example, the controller requires complex operation with a large circuit scale, so power consumption is a key consideration for this chip. Therefore, we apply a suitable low-power circuit technology [2]. On the other hand, the driver and readout chip requires high-speed switching capability. Therefore, we apply an optimum critical current density of Josephson junction.

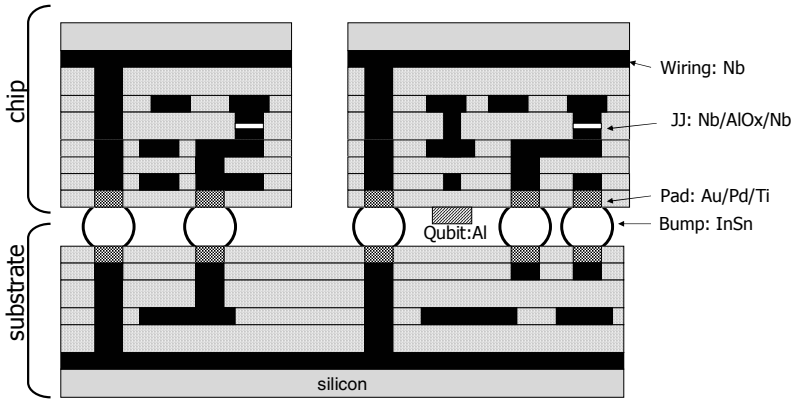

Figure 2. Device structure

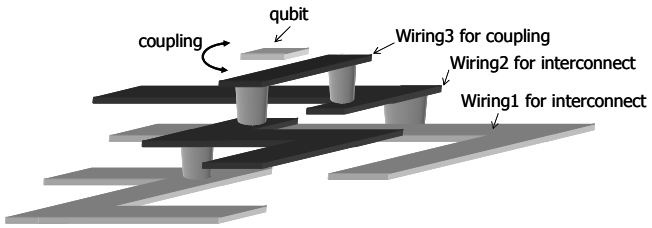

Figure 3. Interconnection scheme

Figure 2 presents a cross-sectional view of the multi-chip module. The chip is connected to the substrate as a facedown flip-chip. Both the chip and the substrate are fabricated with a multi-layer Nb technology. In our current design, the chip has four Nb layers, one Josephson junction (Nb/AlOx/Nb) stacking layer, and one Pd resistor layer. The substrate has three Nb layers. The qubit device is fabricated on the qubit chip, which is another Nb multi-layer chip. This multi-layer structure makes possible separating the functions of each layer. Figure 3 shows an example of an interconnection scheme for the qubit chip. The top Nb layer of the chip is available to be used for either magnetic or electrostatic coupling to the qubit. The other layers are suitable to be used for interconnection because they are relatively far from the qubit. In addition, this multi-layer structure is effective for shielding one layer from another.

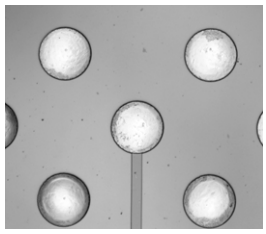

Figure 4. Solder bumps (50 μm diameters)

We have developed a flip-chip bonding technology by superconducting solder bumps. The solder material is a 52%-In/48%-Sn alloy with a melting point of 118°C [3, 4]. Pads are deposited on both the MCM substrate and the chip by sputtering Ti/Pd/Au onto Nb. The solder bumps are then formed on both the substrate and the chip by immersing them into a solder pot. Figure 4

is a photograph of 50-μm solder bumps with a height of approximately 5 μm on an MCM substrate. Attaching the chip to the substrate is accomplished with a flip-chip-bonder. The XY alignment resolution is 3 μm. After bonding, the distance between the chip and the substrate becomes less than 10 μm, which is smaller than the sum of the bump heights on each component. To achieve SFQ pulse communications between chips, we optimized a process for solder bump fabrication and bonding. We confirmed off-chip signal transmission from the multi-chip connection at over 100GHz [5]

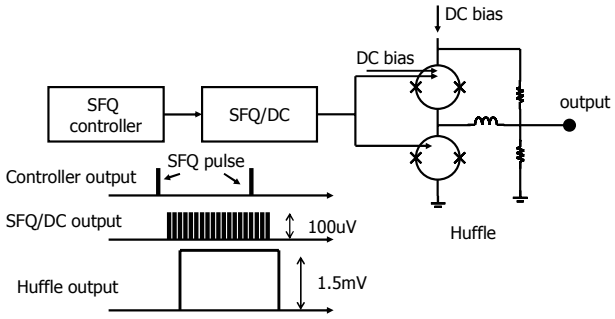

Figure 5. Driver circuit diagram

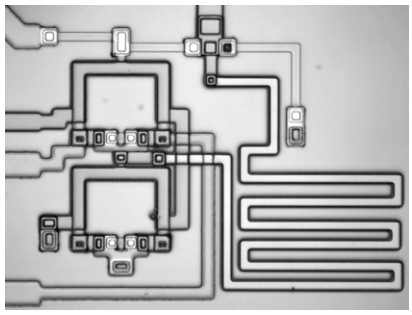

Figure 6. Photograph of fabricated driver circuit

3. Prototype qubit control component

We have also investigated some SFQ control circuits for superconducting qubits, and implemented basic SFQ circuit cells and voltage driver circuits for qubit control. Rectangular waveform signal is often used for controlling a qubit, whereas the signal of the SFQ circuit has a very short pulse nature. A Huffle circuit [6] is a suitable for the driver to convert SFQ pulse to rectangular wave. Using this circuit offers three advantages.

(a) The circuit works under DC bias, while AC-biased circuits are commonly used in SFQ circuits as voltage drivers. To supply DC bias current is easier than supplying AC bias. The influence of the ground noise during driver circuit operation is reduced as compared with using an AC-biased driver circuit.

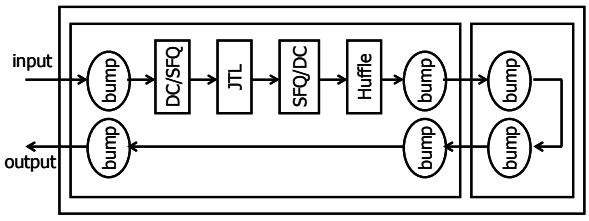

Figure 7. Testing scheme

(b) The circuit can operate asynchronously without any master clock. Thus, we can freely change the on-time length of a signal.

(c) Signal amplitude is over 1 mV, enough to control qubits.

Figure 5 is a block diagram of a driver circuit. The generated SFQ pulse is first converted to a voltage-level signal by the SFQ/DC circuit, and this signal then drives the Huffle circuit, and it generates the millivolt-scale rectangle signal for controlling the qubit. According to a dynamic simulation, this circuit would operate up to 10 GHz. Figure 6 is a photograph of a fabricated the circuit based on the "NEC standard process" [7]. The circuit size is 85 μm x 70 μm, and it consumes about 0.2 μW.

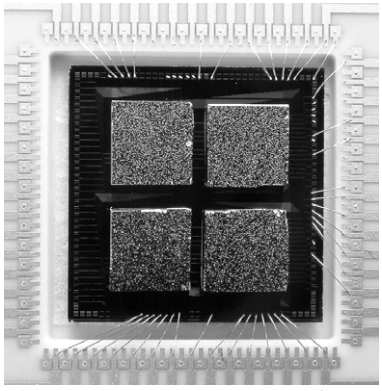

Figure 8. Photograph of test module

Figure 7 is a diagram of the testing scheme. The testing module included two types of chips connected by 50-μm diameter solder bumps to a substrate. One chip contained the DC/SFQ, JTL, SFQ/DC and driver (Huffle) circuits. The other chip was regarded as the qubit chip, but this testing was performed with only interconnection wiring. Figure 8 is a photograph of the test module. It consists of four chips (two pairs of each of the two chips) on the substrate. We confirmed correct operation of the circuit at a 5-kHz pulse repetition rate at 4.2K. Figure 9 presents an example of operational results. The SFQ/DC circuit correctly converted the input return-to-zero signal to a non-return-to-zero signal, and the circuit then amplified the non-return-zero signal.

Towards sub-Kelvin temperature operation, we have to consider the parameter set of the circuit. Critical currents of Josephson junctions are scaled down, while inductances are scaled up, and bias voltage is reduced to make consumption power small. We optimized critical current densities by considering trade-off relations between fabrication availability and operation speed. The critical current density was determined 350 A/cm^2. As a first prototype, we designed a dc/sfq-JTL-sfq/dc circuit set. The scaling factor of inductances and critical current of Josephson junctions is 7 compared with the standard circuit of 2.5 kA/cm^2. Target operating temperature was 0.6K. Figure 10 is a photograph of the fabricated circuit.

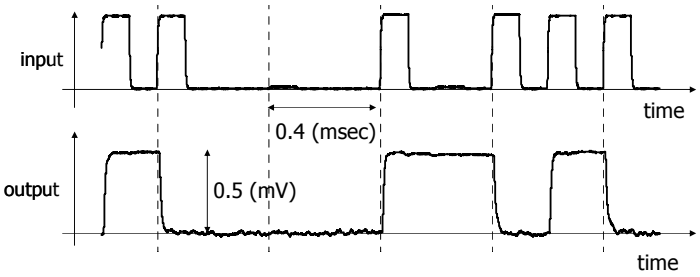

Figure 9. Test results

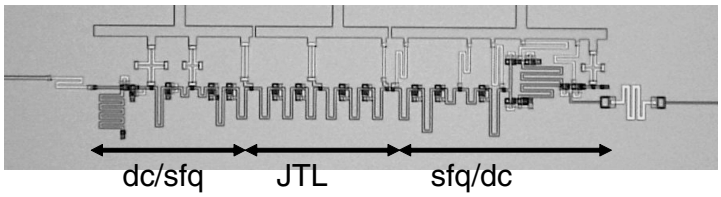

Figure 10. Photograph of fabricated low-Ic with low Jc circuit.

4. Conclusion

We have proposed an SFQ-based qubit control scheme. Our multi-chip module approach provides several advantages for fabricating qubit control modules. We have developed a flip-chip bonding technology and demonstrated a prototype driver circuit operation on a flip-chip module. In addition, we designed a prototype low Ic circuit with low Jc for sub-Kelvin operation.

Acknowledgements
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