

Material Dependence of Initial Failure Rates of Josephson Junctions

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The initial failure rates of Josephson junctions were evaluated with measuring 8K-bit memory cell arrays. Three kinds of junctions; Pb-In-Au/Pb-Bi, Nb/Pb-Bi and Nb/ AlO_x /Nb, showed average initial failure rates of 1.06%, 0.13% and 0.016%, respectively. The Nb/ AlO_x /Nb junctions showed the smallest failure rate, also exhibited high yields in checks of shorts and breaks by using a prober. It is concluded that Nb/ AlO_x /Nb junctions are very promising as elements for large-scale integrated circuits.

1. INTRODUCTION

High switching speed devices with Josephson junctions have been studied energetically and applications to circuits have been developed. As circuit integration increases, the quality of junction material becomes important. Hitherto, the Josephson circuits were fabricated with lead-alloy electrodes¹⁾. But they were unreliable in terms of critical current variation and yield of junction. More recently, the Josephson junctions with refractory materials such as Nb²⁾ and NbN³⁾ were developed, and the high quality of their characteristics was exhibited. Particularly, Nb/ AlO_x /Nb junctions were reported to have excellent junction characteristics^{4),5)}. However, the feasibility of integrated circuits using Nb/ AlO_x /Nb junctions has not been reported.

We fabricated 8K-bit Josephson memory cell arrays with three kinds of junction materials; Pb-In-Au/Pb-Bi, Nb/Pb-Bi and Nb/ AlO_x /Nb. Characteristics of these cells, in particular, the initial failure rate of cells, were evaluated to examine the application to integrated circuits.

2. DESIGN OF 8K-BIT MEMORY CELL ARRAY

Figure 1 is a photograph of an 8K-bit memory cell array. The chip, $5 \times 5 \text{ mm}^2$, contains 8192 cells arranged in 128 columns and 64 rows. The chip has 42 pads to measure I-V characteristics of cells and shorts/breaks in inter-connecting wiring. The layout of a unit cell of the Single Flux Quantum(SFQ) memory is shown in Figure 2. The cell consists of two

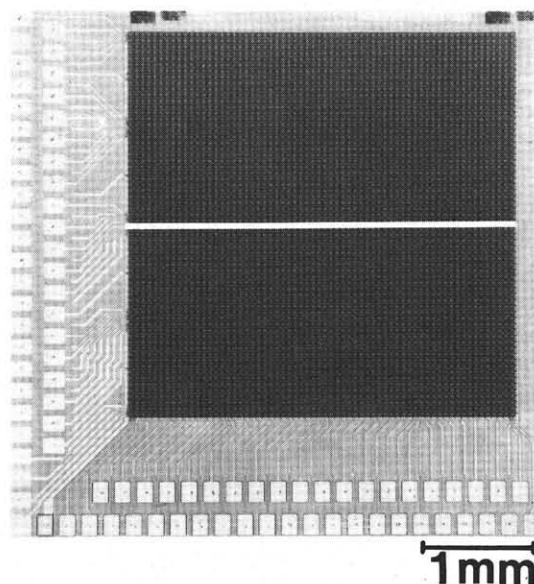


Fig. 1 Photograph of 8K-bit Josephson memory cell array

Josephson junctions and three control lines. The area of a unit cell is $28 \times 55 \mu\text{m}^2$, and that of a junction is $5 \times 14 \mu\text{m}^2$. The line width and the spacing of control lines are both $2 \mu\text{m}$.

3. FABRICATION OF 8K-BIT MEMORY CELL ARRAY

The 8K-bit memory cell arrays were fabricated with Pb-In-Au/Pb-Bi, Nb/Pb-Bi, and Nb/ AlO_x /Nb junctions. The material and the thickness of each layer are shown in Table 1. The patterns were formed by the lift-off process for lead-alloy electrodes and oxygen-doped SiO (SiO_x)⁶⁾ insulator, and by reactive ion etching (RIE) process for niobium electrodes and SiO_2 insulator.

The following sequence for fabrication is common for three kinds of junctions.

- 1) Deposition and patterning of the base electrode(B).
- 2) Deposition of insulation layer(I2) and formation of the junction window.
- 3) Cleaning of the surface on the base electrode and formation of the barrier oxide.
- 4) Deposition and patterning of the counter electrode(CT).

The cross section of a cell is shown in Figure 3. Here, the junction area is defined by the window formed in insulator I2. The conventional Nb/ AlO_x /Nb junctions have been made by depositing the tri-layer(B, barrier, and CT) without breaking the vacuum^{2),4)}. However, we developed a process to fabricate Nb/ AlO_x /Nb junctions with the same junction structure as Pb-In-Au/Pb-Bi junctions.

4. EVALUATION

First, cell array chips were evaluated with a prober at room temperature. In the cell array chips with Nb/ AlO_x /Nb junctions, six chips were observed to have no shorts and breaks in inter-connecting wiring or insulators. But, for the other junctions,

chips passed in the prober test were not observed. Improved yield of the Nb/ AlO_x /Nb cell array is attributed to applying SiO_2 insulator and RIE process instead of SiO_x and lift-off.

The chips with no defects in serial-connected cells were selected to be measured at 4.2K. The I-V characteristics of each 256-cell chain were measured and the numbers of cells

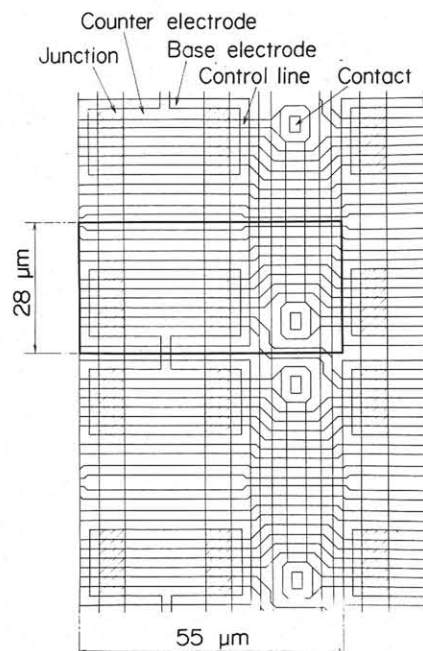


Fig. 2 Unit cell layout.

Table 1 Process parameter of 8K-bit memory cell array.

Layer	Material			Thickness (nm)
	Pb-In-Au/Pb-Bi	Nb/Pb-Bi	Nb/ AlO_x /Nb	
Ground plane (GP)	Nb	Nb	Nb	300
Ground plane insulator	Nb_2O_5	Nb_2O_5	--	30
Insulator (I1)	SiO or SiO_x	SiO_x	SiO_2	300
Base electrode (B)	Pb-In-Au	Nb	Nb	200
Tunnelling barrier	Pb(In)O_x	NbO_x	AlO_x	2
Insulator (I2)	SiO or SiO_x	SiO_x	SiO_2	300
Counter electrode (CT)	Pb-Bi	Pb-Bi	Nb	400
Insulator (I3)	SiO or SiO_x	SiO_x	SiO_2	700
Control line (CL)	Pb-In-Au	Pb-In-Au	Nb	900
Passivation (PA)	SiO	SiO	--	1000

with shorted junctions were counted. The results are shown in Table 2. The measurements were done for three chips with Pb-In-Au/Pb-Bi junction, eight chips with Nb/Pb-Bi junctions and six chips with Nb/ AlO_x /Nb junctions. Among them, the number of perfect chips with no shorted cells were three both for Nb/Pb-Bi and for Nb/ AlO_x /Nb junction. For Pb-In-Au/Pb-Bi junctions, no perfect chips were observed. The average initial failure rate for Nb/ AlO_x /Nb junctions is reduced to about one tenth of that for Nb/Pb-Bi junctions and about one hundredth of that for Pb-In-Au/Pb-Bi junctions. Changing the base electrode from lead-alloy to niobium reduced the failure rate, and the change in the counter electrode further reduced the failure rate.

Next, we examined the quality of I-V characteristics. Figure 4 shows I-V characteristics of a cell with Nb/ AlO_x /Nb junctions. The critical current density j_c is $2200\text{A}/\text{cm}^2$, and the quality parameter V_m is 30mV . This is much improved comparing with 20mV for Pb-In-Au/Pb-Bi junctions and 18mV for Nb/Pb-Bi junctions. Figure 5 shows the distribution of critical currents in the cell array with Nb/ AlO_x /Nb junctions. The maximum-to-minimum spread of the critical currents is within $\pm 10\%$. The standard deviation of the scattering of critical currents is $6=3.5\%$. These values are much smaller than those for Pb-In-Au/Pb-Bi junctions. This is due to stability of refractory Nb electrode and uniformity of pattern size achieved by RIE.

5. CONCLUSION

We fabricated 8K-bit memory cell arrays with three kinds of junctions: Pb-In-Au/Pb-Bi, Nb/Pb-Bi, and Nb/ AlO_x /Nb. Characteristics of cell arrays were evaluated both at room temperature and at 4.2K . The initial failure rates of cells were measured to be 1.06% , 0.13% , and 0.016% for Pb-In-Au/Pb-Bi, Nb/Pb-Bi, and Nb/ AlO_x /Nb junctions, respectively. The spread of the critical currents was also much reduced by using Nb/ AlO_x /Nb junctions. These

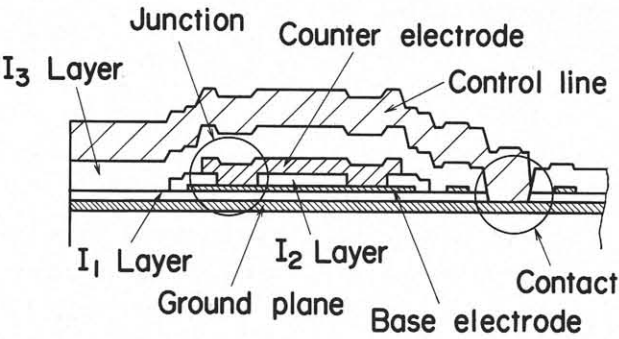


Fig. 3 Cross-section of a cell.

Table 2 Initial failure rates of three kinds of junctions.

Junctions	No. of cells measured	No. of cells with shorted junctions	Failure rate (%)
Pb-In-Au/Pb-Bi	24,576	260	1.06
Nb/Pb-Bi	65,536	83	0.13
Nb/ AlO_x /Nb	49,152	8	0.016

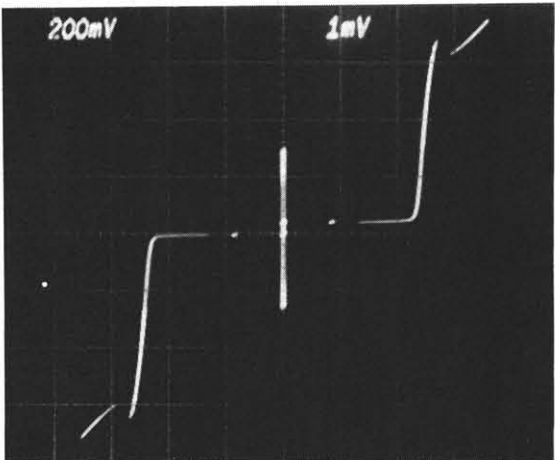


Fig. 4 I-V characteristics of a cell (Ver.; $2\text{mA}/\text{div.}$, Hor.; $1\text{mV}/\text{div.}$).

improvements are due to using refractory Nb for electrodes, SiO_2 for insulators, and RIE for patterning process. As compared with Pb-In-Au/Pb-Bi and Nb/Pb-Bi junctions, Nb/ AlO_x /Nb junctions exhibited much more reliable

characteristics, and are promising as elements for Josephson LSI.

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REFERENCES

- 1) T.Imamura, H.Hoko, H.Tamura, A.Yoshida, H.Suzuki, S.Morohashi, S.Ohara, H.Hasuo, and T.Yamaoka, J. Apply. Phys. 59, 1720(1986).
- 2) H.Kroger, L.N.Smith, and D.W.Jillie, Appl. Phys. Lett., 46, 1179(1985).
- 3) S.Kosaka, A.Shoji, M.Aoyagi, F.Shinoki, S.Tahara, H.Ohigashi, S.Takada, and H.Hayakawa, IEEE Trans. Magn. MAG-21, 102(1985).
- 4) M.Gurvitch, M.A.Washington and H.A.Huggins, Appl. Phys. Lett., 42, 472(1983).
- 5) S.Morohashi, F.Shinoki, A.Shoji, M.Aoyagi, and H.Hayakawa, Appl. Phys. Lett., 46, 1179(1985).
- 6) H.Shibayama, S.Hasuo, and T.Yamaoka, Appl. Phys. Lett., 47, 429(1985).

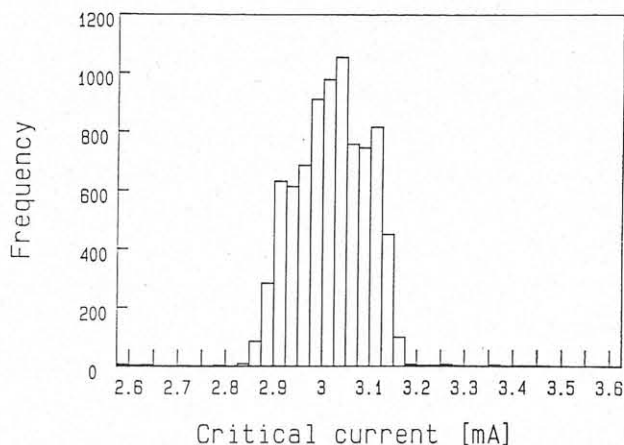


Fig. 5 Histogram of critical currents of 8K cells.