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# Experimental Investigation of Two-Dimensional Arrays of Ultrasmall Josephson Junctions

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**Abstract.** We have investigated two-dimensional arrays of low capacitance (C) aluminum Josephson junctions with varying values of the normal state resistance $R_N$ and the ratio $E_J/E_C$, where $E_J$ is the Josephson coupling energy and $E_C$ is the charging energy ($e^2/2C$). For low resistance, $R_Q/R_N>>1$ ($R_Q=h/4e^2=6.5k\Omega$) and $E_J/E_C>1$, the Josephson current prevails. When $R_Q/R_N<<1$ and $E_J/E_C<1$ the arrays are dominated by the Coulomb blockade. In an intermediate region of the parameter space, $R_Q/R_N\leq 1$, $E_J/E_C\approx 1$, we find a "back-bending" I-V curve with negative differential resistance. For the Coulomb-blockade-dominated arrays we find that the low voltage conductance decreases strongly with lowered temperature but find no evidence for a Kosterlitz-Thouless-Berezinskii phase transition of charge unbinding. On the contrary, we find no significant difference between a 2-D and a 1-D array.

## Introduction

In order to explore the parameter space for 2-D arrays of small tunnel junctions we have measured I-V characteristics of a large number of arrays with different parameters $R_Q/R_N$ and $E_J/E_C$. We have produced 18 arrays with resistances ranging from 1 kΩ to 1 MΩ for the individual junctions. The ratio of $E_J$ to $E_C$ ranged from 0.003 to 7.5. Here $E_C$ is estimated from the nominal junction areas, and it corresponds well with the measured offset voltages. $E_J$ are calculated from $R_N$ and the superconducting gap $\Delta$, $E_J=(R_Q/R_N)(\Delta/2)$. Similar measurements were done by Geerligs et al [1].

A Kosterlitz-Thouless-Berezinskii (KTB) phase transition may occur in 2-D arrays of Josephson junctions. An interesting duality between vortices and charges exists in these arrays. The KTB transition can describe the vortex unbinding transition from the superconducting state when $E_J/E_C>>1$ [2], and the charge unbinding transition from the insulating state when $E_J/E_C<<1$ [3]. Evidence for the charge unbinding transition in arrays where $E_J/E_C\approx 0.5$ is claimed in recent experiments [4].

## Josephson Current vs. Coulomb Blockade in I-V Curves. Back Bending

Square arrays with sizes from 20x20 to 86x86 junctions were fabricated using electron beam lithography and a suspended bridge technique. The junctions of the arrays were made of aluminum and they were measured in the superconducting state. Going from the upper right corner to the lower left corner of the phase diagram ($R_Q/R_N$ vs. $E_J/E_C$, see Fig.1) we encounter different types of I-V characteristics. Note that this is not a true Schmid diagram since we plot $R_Q/R_N$ and not the real damping $R_Q/R_S$, $R_S$ being an ohmic shunt resistance seen by the junction.

In the upper right corner of the diagram (region A), the I-V curve shows the general Josephson behavior, however there is a finite slope of the "super"-current due to the relatively strong charging energy leading to phase fluctuations. Going downwards/leftwards (region B) a small "foot" starts to develop at the origin due to the stronger Coulomb blockade. In a region where $R_Q/R_N<1$ and $E_J/E_C\leq 1$ (region C), the "foot" has developed to a strong Coulomb blockade and the curve starts to bend back towards the current axis due to the Josephson coupling. At higher currents, the voltage increases again due to Zener tunneling. In the lower left corner of the diagram (region D), the Coulomb blockade is dominating completely. In the region where $R_Q/R_N<<1$ and $E_J/E_C\leq 1$ (region E), the I-V characteristics show a behavior similar to the arrays in the region B, but with a sharper Coulomb blockade. The crossover to this region from the back-bending region is not yet understood, since one would expect to strengthen the back-bending instead of weakening it when $R_N$ is increased. The behavior in the other regions is qualitatively what is expected from theoretical arguments. Where our data overlap with that of ref.1 we observe a good agreement.

## Comparison between 1-D and 2-D Arrays

We compare measurements of 2-D and 1-D arrays for $E_J/E_C>>1$ and $R_N>>R_Q$. As no KTB transition occurs in 1-D, this comparison should allow us to see that part of the transition which is truly due to 2-D effects. For the 1-D array R=88kΩ, and $E_J/E_C$ is estimated to be 0.022. For the 2-D array, R=100kΩ and $E_J/E_C\approx0.018$. The low bias conductance $(R_L)^{-1}$ is plotted in Fig.2. In both the normal and superconducting cases, there is a striking similarity between the 1-D and 2-D data. The shape of the curves for the 2-D array is similar to that found in Ref.3. The very similar temperature dependences of the low bias conductance in the 2-D and 1-D case for both the superconducting and normal states, suggest that the transition to the insulating state is governed by similar charging phenomena in both the 2-D and 1-D arrays, and that no intrinsic 2-D character of the transition is present. This observation is not remarkable considering the small charge soliton [5] length (M≈10 junctions). However, our 2-D array should have a larger value of M than previous experiments [4] where evidence of a 2-D transition was claimed.

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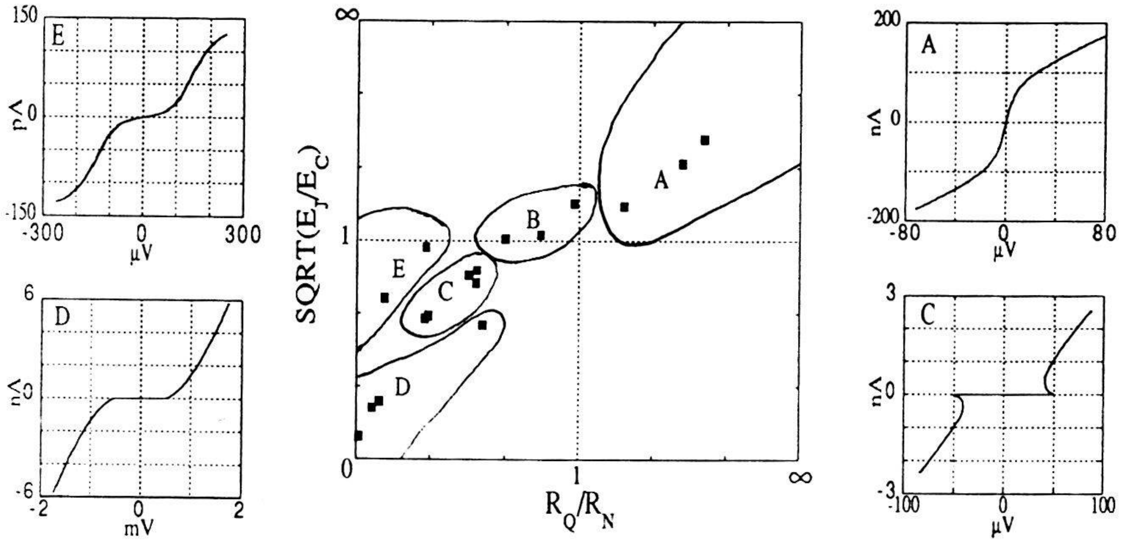


Fig.1. Representative I-V curves for different regions of the diagram relating $E_J/E_C$ to normal state resistance. Curves in the region B are similar to those in the region A but with a slight Coulomb blockade. The curves were registered at temperatures of about 40 mK.

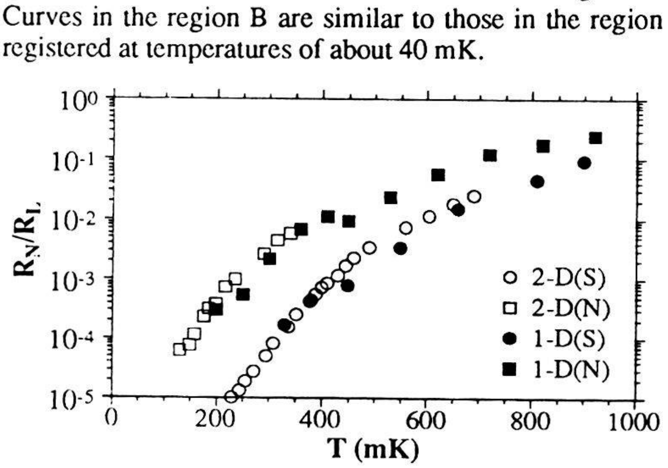


Fig.2. Normalized low voltage conductance as a function of temperature. Open symbols denote 2-D arrays, filled ones 1-D arrays with similar junction parameters. Circles give superconducting state data, squares normal state data. The normal state was obtained by applying a large magnetic field.