

# REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)  Our research group is involved in the use of a millikelvin Scanning Tunneling Microscope (mK-STM), developed in previous grant periods.				
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***Foreword***

We use high resolution STM at millikelvin temperatures (mK-STM) for allow imaging, spectroscopy, and control of the quantum wavefunctions of the electrons in metallic nanostructures. This work is directed at expanding our understanding of the quantum physics of electrons in metallic nanostructures, of effects of electron correlation in important materials, and of dopant atoms in semiconductors for the realization of quantum computing.

***Statement of Problem***

To develop a millikelvin STM capable of operation at high-fields with atomic-resolution spectroscopic mapping and its application for wavefunction imaging studies of important systems and to apply this technology to wavefunction imaging studies.

***Summary of Achievements***

**1. Millikelvin STM Development**

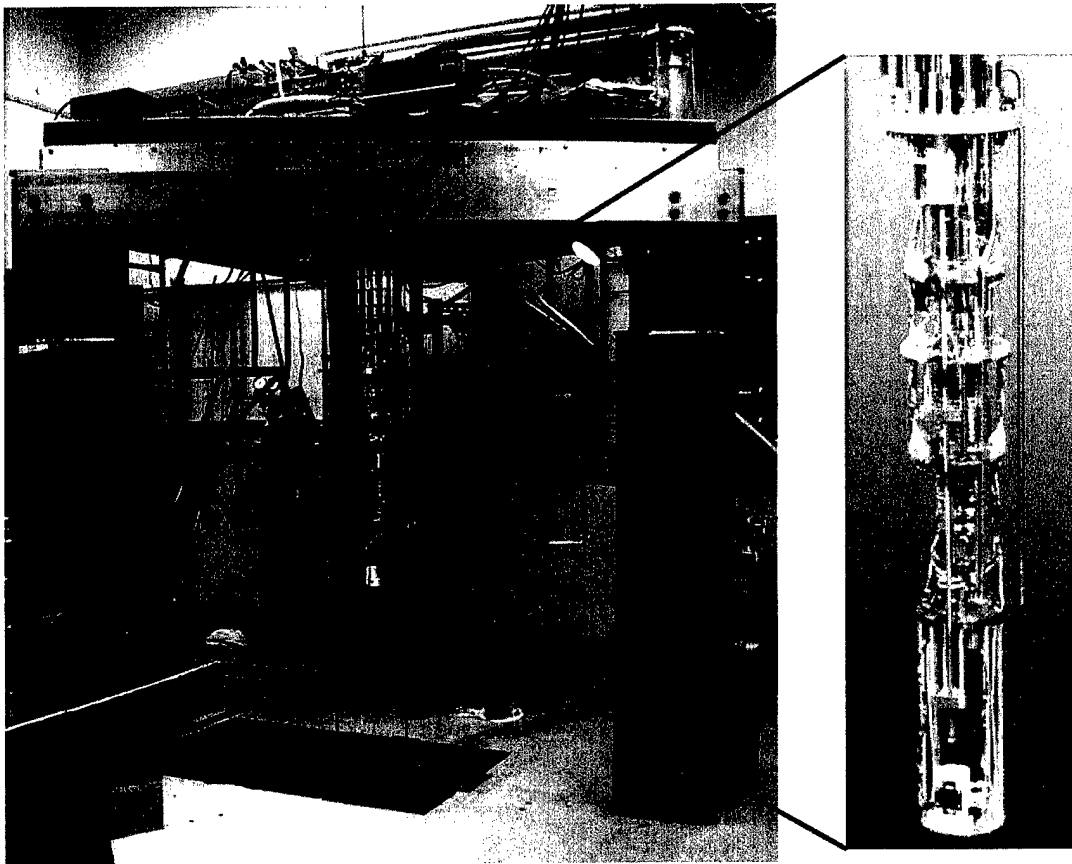


Fig.1a. Picture of the vibration isolation cryostat including the dilution refrigerator with STM head suspended below the mixing chamber.

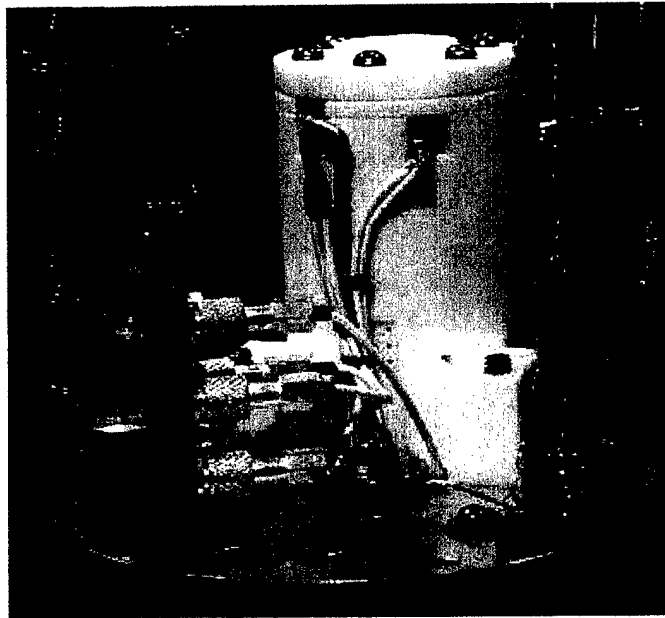


Fig. 1b. The STM head suspended below the mixing chamber.

The first achievement was successful development of a system (Fig. 1a and 1b) that allows atomic resolution spectroscopic mapping STM at temperatures down to 12mK in fields up to 9 Tesla. This is the only system of this type in the world.

## 2. $\text{Sr}_2\text{RuO}_4$

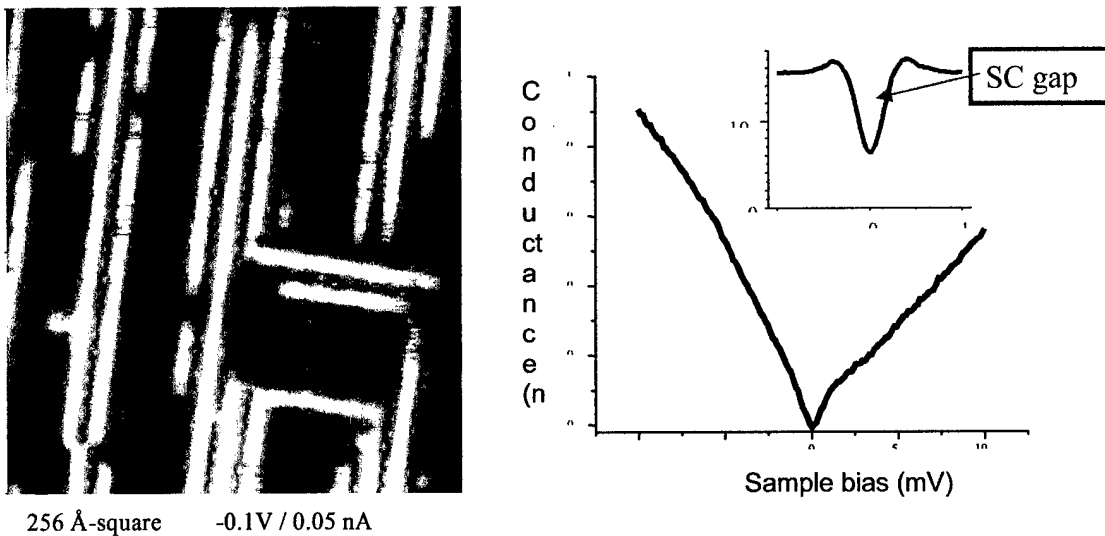


Fig. 2a. Image of the RuO surface of  $\text{Sr}_2\text{RuO}_4$ . b. Spectra on this surface showing the superconducting quasiparticle spectrum (insert).

We used the system for atomic-resolution scanning tunneling spectroscopy to study the spectrum of quasiparticle states in superconducting  $\text{Sr}_2\text{RuO}_4$ . This material displays an exotic form of superconductivity at temperatures below 1.45 K. As a result of extensive studies, both experimental and theoretical, a model for the p-wave symmetry of the superconducting order parameter (OP) is beginning to emerge. Because of the

independence of the spin susceptibility on temperature below  $T_c$ , the Cooper pairs are believed to be in a spin triplet 'equal spin pairing' (ESP) state. Muon spin rotation studies show a time-reversal-symmetry breaking (spontaneous magnetization) signal which is also consistent with spin-triplet superconductivity. The temperature dependence of the quasiparticle spectrum, which we measured here for the first time, is consistent with a superconducting order parameter exhibiting a line of nodes. Further, in magnetic fields  $H < H_{c2}$ , a vortex lattice, square and oriented parallel to the  $\langle 110 \rangle$  of the  $\text{RuO}_2$  lattice, is detected by spectroscopic imaging. Each vortex exhibits one flux quantum, with a rotationally symmetric core and a strong zero-bias conductance peak.

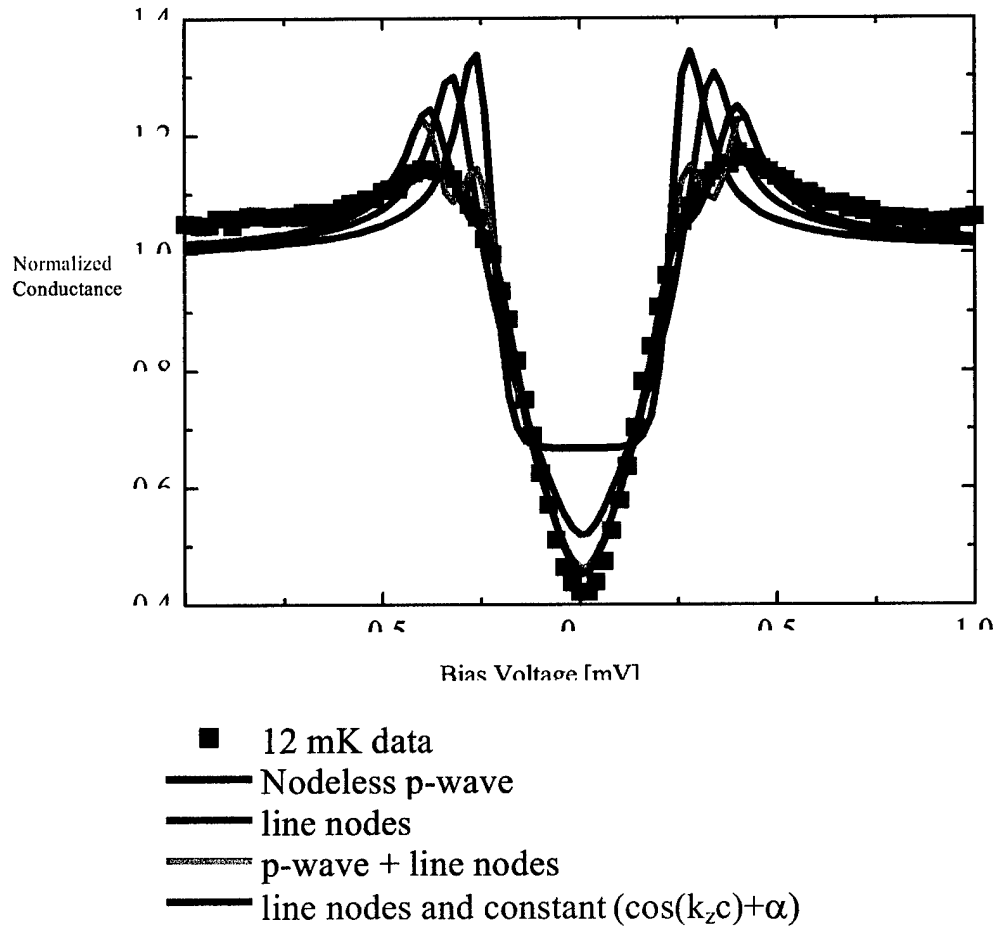
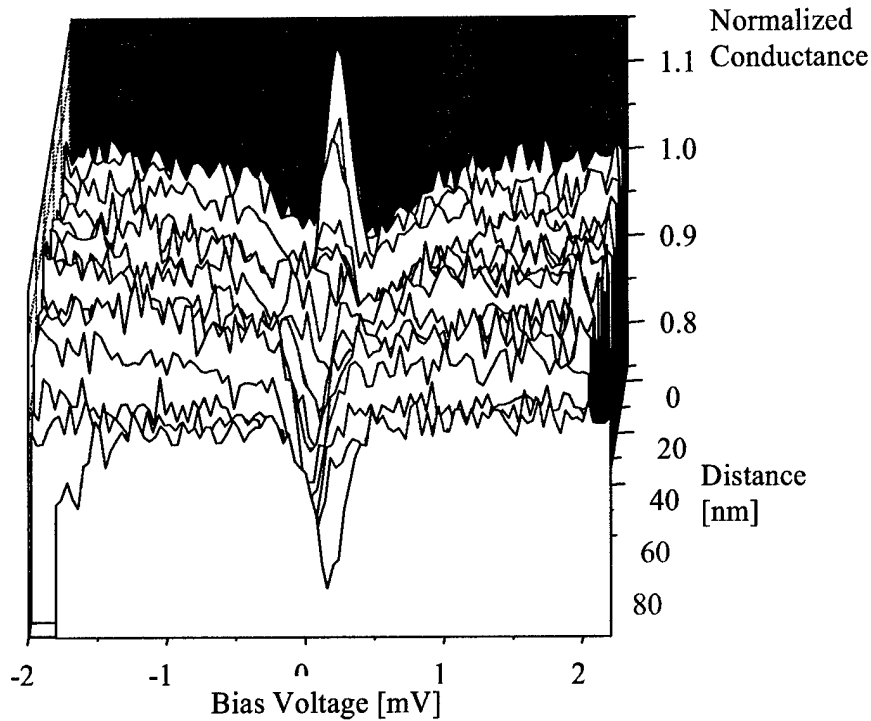


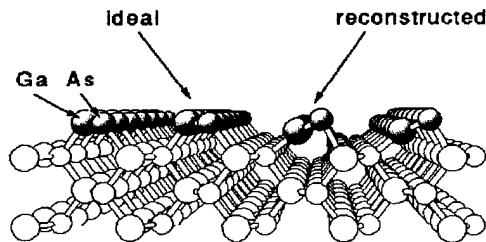
Fig. 3. Comparison of different model fits to tunneling spectra of  $\text{Sr}_2\text{RuO}_4$  at 12 mK. Horizontal line nodes in momentum space appear to be the best fit.

Fig. 4. Dependence of spectra on distance measured form the center of a vortex core.



### 3. GaAs

We used the millikelvin, high-field, scanning tunneling microscopy (STM) to study the fundamental physics of bound electronic states at individual dopant atoms in a semiconductor. Although much has been said and written about electronically addressing single quantum states at dopant atoms in semiconductors, no experiments have been carried out and almost nothing is known about the applied physics of this situation. Therefore our studies were initially directed towards direct detection and study of the Zeeman-split bound-states at individual dopant Te atoms (in high magnetic fields at very low temperatures) as a test case. We could identify the location of the dopant atoms, measure their spectrum and locally map the wavefunction of the donor state with spectroscopic mapping.



GaAs (110) ideal / reconstructed surface

Fig. 5. Schematic of <110> cleave surface of GaAs

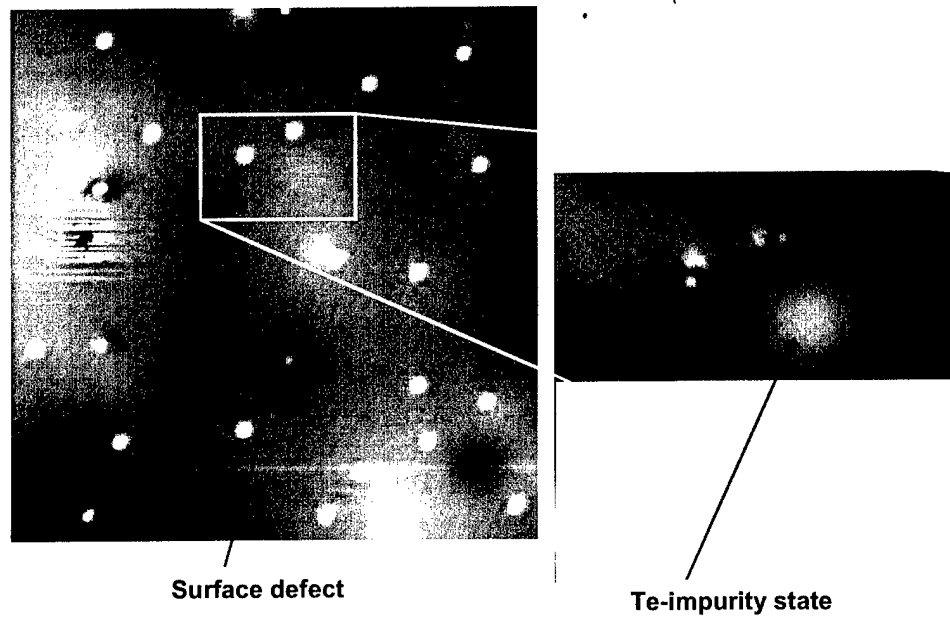


Fig. 6. Images of <110> surface of GaAs showing surface electronic defect states and the location of the Te donor atom.

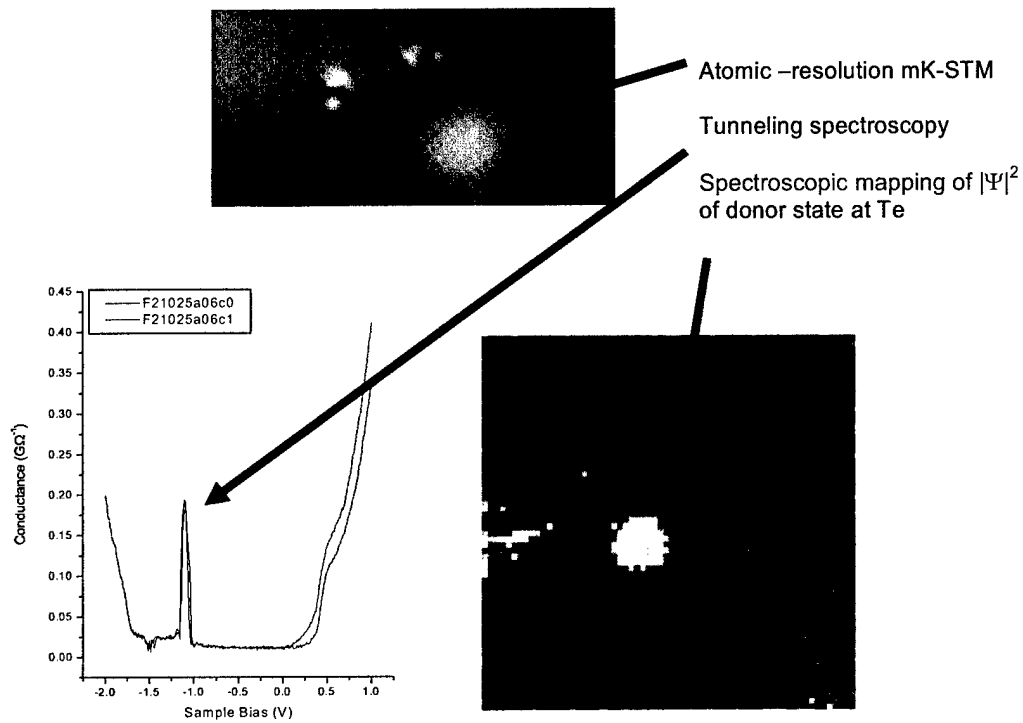


Fig. 7. Combination topographic image, spectrum at the Te site, and wavefunction image of the Te donor state (taken at 25 mK).

### 3. NbSe<sub>2</sub>

This is a low temperature superconducting system with almost perfect atomic surfaces. We intercalate magnetic impurity atoms (Fe) between the planes and then, when we cleave it, they remain on the top surface. We can manipulate these atoms to make magnetic nanostructures whose electronic wavefunctions we are now studying by spectroscopic mapping at mK temperatures.

#### *Topography+ Vortices*

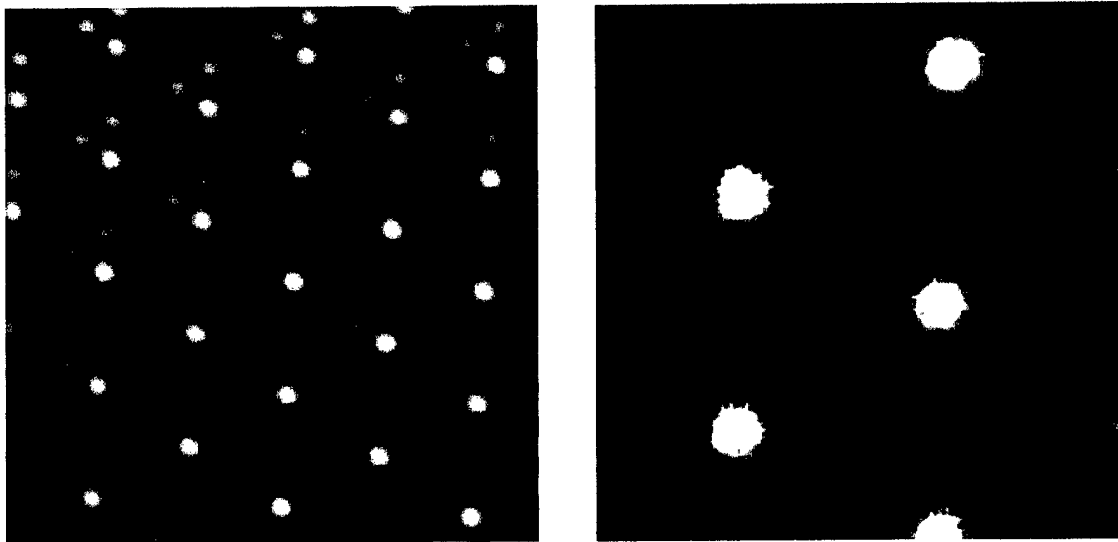


Fig. 8. a 250 Å square topographic image of the Se surface of NbSe<sub>2</sub>. Each Se atom, plus the charge density wave modulations, are seen. b. Wavefunction image of the vortex core states in a 1200 Å FOV at B~2 tesla.

#### *CDW + Fe atoms*

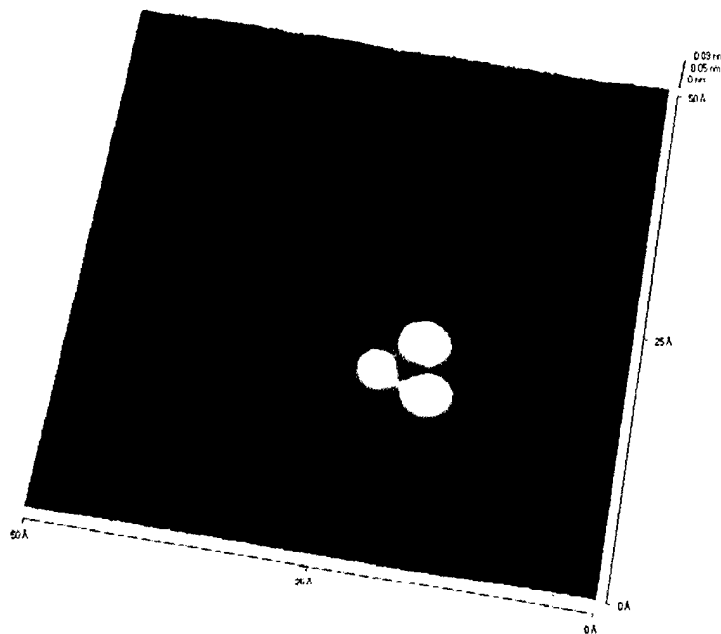


Fig. 9. A magnetic cluster of 3 Fe atoms assembled on the NbSe<sub>2</sub> surface.

## *Publications*

1. "Effects of Individual Ti atoms substituted for Sr in  $\text{Sr}_2\text{RuO}_4$ " B. Barker, S. Dutta, C. Lupien, Y Maeno, and J. C. Davis, *submitted to Proceedings of LT23, Physics B*.
2. "Temperature- and Field-dependence of the Quasiparticle Spectrum of  $\text{Sr}_2\text{RuO}_4$ " C. Lupien, B. Barker, S. Dutta, Y. Maeno and J.C. Davis, *Submitted to Phys. Rev. Lett.*
3. A millikelvin high field spectroscopic mapping STM, B. Barker, S. Dutta, C. Lupien, and J. C. Davis, Submitted to *Rev. Sci. Inst.*,
4. Switching of the electronic configuration of defect states on the surface of GaAs, B. Barker, S. Dutta, C. Lupien, Y Maeno, and J. C. Davis, *in preparation*.

## *Personnel*

Dr. Barry Barker (now at LPS, University of Maryland, College Park, Maryland).

Dr. Christina Lupien (moving to Cornell University to my new lab in June 2003).

Sudeep Dutta.

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BSc 2003