FINAL REPORT
SBIR Phase I
Contract # F0-8630-95-C-0036

"Polymer Room Temperature Superconductors Near-term Applications"

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OVERVIEW

The feasibility study was very successful in exploring a wide variety of applications of the highly conducting Ultraconductor™ materials.

APPLICATIONS PROPOSED

- SMES - Feasible
    - Wire required
    - Not easily scaled to small size
- Computation and Magnetic sensing
    - Experiments designed
        - Josephson radiation
        - Niobium ring
- Magnetic Shielding - feasible in Phase II

APPLICATIONS DISCOVERED

- Connectors - high current
- Batteries
- Supercapacitors, ultracapacitors

ADDITIONAL ACCOMPLISHMENTS

- A new MPI lab was set up to do the measurements
- MPI started working with the basic (non conductive) material to determine production issues.
- The samples were found to be fragile
- Purdue University is now involved in measurements.
- Atomic Force Microscopy (AFM) has been applied by LANL and Digital Instruments
- Phase II proposal (Summary in Appendix F)
- Test Sets designed (Appendices A & B)
- Probe development (Appendix D)

INTRODUCTION

This is the final report and deliverable Re: SBIR Contract # F0-8630-95-C-0036.

The contract was awarded by the AF to explore a new material - a new technology - based on discoveries made about 1985 that certain polymers had highly conductive regions; The material was subsequently developed into thin film samples suitable for experiments.

Previous experiments had measured very high current density, conductivity 5 orders of magnitude better than copper, and violation of the Weideman Franz Law (thermal and electrical conductivity are proportional); these results are similar to the properties of superconductors and it was proposed to explore the characteristics and potential applications of the Ultraconductor samples.

Areas of interest proposed for the study were Energy applications, Computation, Magnetic Sensing and Magnetic Shielding.

The work on the contract was done by MPI at its office in Sebastopol, and its Laboratory in Sebastopol. This work was supplemented by experiments at LANL, Purdue University and Stanford University, and analysis of the superconductivity properties by Dr. Frank Chilton, and of the thermoelectric properties by Dr. Michael Nicholaou.

It was found that the energy applications are feasible - for example in the form of Ultraconductive Magnetic Energy storage system (UMES) - however, further work on this should be postponed until sufficient lengths of wire is available. It is likely that long lengths of wire will be achieved as more is understood about the conduction mechanism in the polymer.

The Computation and Magnetic Sensing applications both would depend on quantum effects such as Josephson tunneling in Superconductors. MPI found it very difficult to make even simple measurement on the polymers, such as conductivity or current density, since the samples are so fragile (being only 10 microns thick) and the regions are so small - about 1 micron diameter. Hence we are attempting to measure the characteristics of conducting threads 1 micron in diameter by 10 microns long. It was found to be too small a volume for a SQUID. The result of the study in this area is to propose an experiment which would test these areas for Josephson Radiation. It was determined that regular SQUID measurements would not work, even if the material is superconducting - and another experiment is proposed using the sample on a Niobium substrate.

The fourth area of interest, Magnetic Shielding, is the one with the most immediate application, since it can be done without the development of wire, and does not require superconductivity but only highly conductive domains. The development work here is to create thicker films and higher densities of conductive regions. Both of these are reasonable objectives for a development program.

As a result of the research on the above Areas, there were several results which were not anticipated, described below under "Results of Research". The ability of the film to carry high current densities, both in individual channels and over an area of about 1 square cm, was clearly established. Special Test Sets were designed to demonstrate this since it is highly significant for applications. Furthermore, it was shown that two polymer samples in contact formed a connection and could carry high currents (2000 amps).

The thermoelectric properties of the polymers were analyzed, and show promise of improving efficiencies in this field.

These results lead to the investigation of commercial applications - in batteries, supercapacitors, and connectors.

To be successful in these areas it is necessary to increase film thickness from the 10 microns typical today, to 100 microns or more. There are several approaches to this described in the phase II proposal.

It also became obvious that the creation of wire is a key to the largest markets, and we started to do work in understanding the basic materials and fabrication techniques. One approach which would give great flexibility if realized is the use of powder technology. This could not only lead to wire, but many other applications based on bulk conductivity.

AREAS OF INTEREST

A) ENERGY

Energy storage is the most obvious use of a superconductor - filling in the gap between batteries and capacitors.

It is not possible to do a definitive study on the Ultraconductor samples in this role because the necessary wire is not yet practical, and hence its characteristics cannot be measured. However it is clear that when the necessary length of Ultraconducting wire is available a SMES will be possible.

The following analyses may be made:

Conductivity model

The conductivity of the Ultraconductor samples is very high - over 10^11 S/cm by one estimate and 10^22 S/cm by a magnetic technique. Hence, when wire is obtained it is possible that the resistance will be found to be zero. In this case the design of energy storage coils is similar to that of a superconductor, without the problems of refrigeration.

Assuming that the resistance is not zero, the energy storage will still be useful where the time constant of decay of the coil greatly exceeds that of the specified storage time. In many cases SMES units are used for power conditioning - taking care of "drop-outs " of a few cycles which are a common occurrence, or used to change the power factor. However, long term storage such as nighttime storage for use in the day would require that the resistance be zero.

Energy Capacity model of the SMES.

The initial approach is to look at general parameters. It became clear that a small SMES will not compete with batteries in energy capacity. For example, a SMES with 1 inch diameter x 2 inches length (similar to a "C" or "D" cell) at a field of 5 Tesla holds only 138 joules or 40 mWh. Hence, the SMES would be used only when high charge/discharge rates are required.

Magnetic field model of the SMES.

Inductance is required for energy storage. The polymer appears to have a high current carrying capacity - 10 to 80 amps in a 1-2 micron diameter region. Assume that the region needs to be surrounded by .5mm of material (1mm diameter) to provide the dipoles and a support structure. The capacity of a wire would then be 1000 to 8000 amps per sq. cm. However, it is conceivable that only 100 microns diameter is required, giving 100 times that current density.

Electronics analysis for the SMES.

The room temperature electronics may be similar to that for low temperature superconductors apart from the electronic switch. Energy storage requires a switch, preferably which is superconducting when closed. Low and "high" temperature superconductors can use the difference between "normal" and superconducting as a switch mechanism which is not easily available in the polymers, since there is no Tc. Another approach is to make the contacts of a relay (or similar device) from the polymer film. This was simulated in the capacitance discharge experiment, where the contacts carried up to 2000 amperes, in contrast to 16 amperes maximum reported for tin-coated lead contacting a niobium sheet. (Ref: Gaule et al, DDC #AD6121B, June 1946) Hence a combination of a polymer coated relay, in parallel with another switch (to avoid arcing on opening) is feasible.

B) COMPUTATION

Superconductors may be used for high speed computation, generally using the Josephson quantum effects in switching devices. The study explored many approaches to showing that the polymers might exhibit quantum effects but the experiments proposed were beyond the scope of this project.

There is reason to believe that Josephson Junctions (JJ) are possible, but no proof at this time.
Three indicators are:

a) The non-linear form of Volt-Ampere Characteristic (VAC) when recorded at room temperature corresponds to the form a JJ would exhibit - however, this is masked by the electrode resistance.

b) In I. Schlimak's paper (JETP Letters, 1990) the picture of non-linear VAC at 3.6K coincides exactly with the known JJ effect. In this case the electrodes are in the superconducting state, and do not disturb the measurement.

c) Theoretical considerations: The conducting thread is surrounded by a sheath of polymer dipoles - hence contact to the electrodes is by tunneling through this sheath. This tunneling is quite typical for the creation of a JJ.

Having explored the various approaches to searching for quantum phenomena, two experimental techniques have been designed.

a) Lay down the polymer film on a substrate of Niobium. This does not allow a room temperature test, but could show quantum properties at the temperature that Niobium superconducts (less than 10K). This Niobium polymer sample may be bent into a ring containing a polymer link. If the polymer behaves like a conventional superconductor, then currents induced in the ring will persist. If it behaves as a "weak link" there will be quantum effects, and an analysis of these effects may show whether it is acting like an insulator, or a conductor.

b) A copper electrode on a polymer sample on a copper substrate may be modelled as: metal-TR-SP-TR-metal, where TR is a tunneling region at the contact point, and SP is the superpolaron in the polymer matrix. This model is not a conventional ring with a weak link, used for analysis of Josephson effects. However, if the superpolaron acts as a superconductor it is possible that the breaking of Cooper pairs at the TR (acting as a "weak link") will exhibit either Josephson radiation or the band gap observed by Giaever. Our consultant, Dr. Frank Chilton, recommended using the reverse effect - shine a laser on the junctions and measure the voltage. This is much more practical than applying microvolts and trying to measure GHz output.

C) MAGNETIC SENSING

Magnetic sensing using superconductors is also dependent on the quantum effects, the same as computation, so the discussion above applies. Initially it was assumed that a SQUID could be used to test for superconductivity, implying quantum properties, but this proved an oversimplification.

The normal approach to checking superconductivity using a SQUID, is to sweep the temperature through the transition to the normal state.

One of the difficulties in measuring the present samples is that the superconducting regions are only 1 micron in diameter, with a volume of 1 in 10,000 of the material. SQUIDS are capable of measuring this small percentage, but only if there is a transition to "normal" which then gives the background field. In the superconducting polymers there is no Tc, (it appears to be superconducting until the material is destroyed by the heat), hence the typical approach will not work.

The SQUID is checking diamagnetism. Since the Ultraconductors are quasi 1-dimensional, they do not carry the circulating currents that a bulk superconductor carries to produce the diamagnetic response. They will typically measure as slightly ferromagnetic.
Samples were tested in a SQUID at Stanford University with null results.

An experiment was done in 1992 with a magnetic balance, which showed intermittent diamagnetic responses over a period of days. The theoretical explanation is that conducting filaments within the film form rings in a random way, allowing circulating currents to flow. This random movement is less likely in the newer, more stable polymers, and would also be inhibited by the low temperatures utilized in a SQUID, if an attempt were made to use a SQUID to replicate the phenomena.

D) MAGNETIC SHIELDING

It was determined that this application was very feasible and should be pursued in Phase II. Electromagnetic shielding can presently be fabricated using existing conducting polymers. It is anticipated that the performance will be greatly improved by employing these superconducting polymers. Either thick films or short fragments of wire are necessary for this application.

RESULTS OF RESEARCH

MPI designed and built special Test Sets to carefully measure the current capacity of the films. What would appear to be a simple task is complicated by the constant possibility of piercing the film and shorting the probe directly to the substrate.

High current tests.

This test circuit uses a capacitive discharge technique and is characterized with a calibrated CVR.

The "Multichannel" test set shows that the polymers can handle 2000 amps in approx 1 sq. cm. This is true both for a single layer and for two layers in contact (as in a connector).

The Single channel test set required experimenting with various probe designs in order to measure a single channel without damaging the polymer, and with some assurance that the probe is not making direct contact with the substrate. The probe tip is a wide (4 mm) flat insulator with a small (75 micron) coplanar conductor - similar to coax. It appears that the conducting regions can carry 100 amps.

The test sets and procedures are described in detail in the Appendix.

Pressure tests

MPI also carried out tests to measure the pressure at which the film would start conducting. This was generally in the region of 5 kilograms/cm ^2.

Solartron:

Samples were sent to the Solartron laboratories, to be characterized by Electrochemical Impedance Spectroscopy (EIS).

Solartron performed the measurements with a steel contact of diameter .658 cm. This showed conducting areas with an impedance of between 100 and 200 milliohms from 0 to 10 MHz, where the apparatus became conductive. In the nonconducting areas, the measurement of capacitance under the probe showed the dielectric constant to be 3.56. These results are consistent with other measurements and did not show any new properties.

Purdue University:

Dr. McElfresh, and his team have made preliminary scans with the AFM, and run I-V curves; it is too early to draw any conclusions - some curves look interesting, but this could be the result of artifacts of the equipment or test set up. He will procure conjugated conducting polymers to use as a comparison.

Dr. McElfresh also has plans to continue this research: Spacial resolution of the conducting properties will be an important goal. The I-V characteristics will be studied utilizing a special probe with a spherical electrode which can be rolled across the film, with controlled pressure. A similar probe will be used to map C-V properties. This is used to study the conductivity to determine if it is ionic, or otherwise characterize the carriers. The SPM will also be used for Magnetic Force Microscopy (MFM), which can spatially map the magnetic field.

AFM measurements;

Dr. M. Hawley of LANL has started an investigation. The samples are being scanned for electric field and magnetic response. The results are not yet available, because of equipment problems. Digital Instruments did some scans (see Appendix) which show that the conducting areas are of the order of one or two microns in diameter.

Thermoelectric Analysis:

Dr. M. Nicolaou has done a preliminary analysis of the thermoelectric application of the polymer films. Superconductors have been shown by Goldsmid, in theory and in practice, to be superior to normal conductors as one leg in a thermoelectric device. That assumes that the superconductor is of adequate thickness. Nicolaou reviewed the experimental results of Grigorov and expects the polymer to create a significant improvement in the efficiency, by substituting it for the p-type material as a passive leg. The p-type materials have also the problem of tending to become n-type as the temperature rises, lowering the efficiency.

Connectors:

Samples were made on PCB's to facilitate connector tests at Wright Labs. The samples were not perfect because of a reaction between the PCB and the polymer cross linking. To create future samples for testing the voltage breakdown, it will probably be easier to create an Ultraconducting film on glass or ceramic, with a thin layer of gold in two areas, separated by .25 or .5 inches. This will be worked on in the coming months.

Sample Fabrication:

A SMES cannot be made without wire. Concepts were developed for creating thick film and, ultimately, films thick enough to lead to wire. Thin films of polypropylene have been made on flat discs. To ensure a highly polished surface for the substrate (any protrusions can lead to false appearances of conductivity) discs prepared for disc drives were procured, made from nickel on polished aluminum (prior to the magnetic coating).

Three methods of coating are being developed, utilizing a 1% solution of polymer - spinning, dipping, and spraying. So far only the "spun on" coatings have been prepared, in sub-micron thickness. The submicron coating, which will often be made as a step in quickly checking out a material, created its own problems of conductivity measurement - the surface of the electrode pressed on the film has to be exceptionally smooth to avoid puncturing the film - much smoother than for the 6-10 micron films we have been testing. A soft Indium surface may be required.

Powder Technology.

One approach to a new method of fabrication is powder technology. Besides the advantages inherent in this technology in general for fabricating wire and other shapes, the large area to volume ratio created in a powder is expected to enhance some of the steps required in inducing conducting threads in the polymer. It could be done by blowing powder on a very fine grid - possibly made of the same polymer, or an isotactic version for strength. For some polymers it may be possible to grind the powder, or to grind it mixed with a hard powder - since many of the polymers are soft. It may also be possible to grind it by reducing the temperature below the glass point.

There are several ideas in the Phase II proposal which relate to powder technology - namely, dividing the film, separating the conducting elements, and rebonding it. This scenario could be more likely to work than initially starting with a powder, before conductivity is created. The reason is that, whereas the final conducting region may only be the size of a grain of powder, the conducting thread has probably been formed from superpolarons drawn from a much larger region. Hence the approach of first forming the conductor, stabilizing it, and then creating a powder has a better chance of success.

At that point the powder can be thermobonded or swaged; and this could lead to wire or even bulk conductivity.

PHASE II OUTLINE

For Phase II the emphasis shifted to focusing on the more immediate commercial possibilities for the conducting polymers. The term Ultraconductor™ has been adopted as a trade mark, to distinguish the product from both low conductivity conducting polymers and from high temperature superconductors. It is becoming clear that the immediate objectives should be to use the films - either as they are, or in thicker versions, and to utilize the high conductivity, which is measurable. The development of wire, and the measurement of thermoelectric and quantum properties are still in the realm of science.

As a result of the Phase I, a Phase II proposal was requested, to be focussed on the use of the film in batteries and in supercapacitors and ultracapacitors, its use in high current contacts, and in electromagnetic shields. Phase II will address these by developing both powder technology and thick films. Phase I results indicate that these are feasible short term commercial goals, and there has been definite interest from commercial companies in these fields.

A number of companies are potential strategic partners with regard to these polymer superconductors and will be an increasing target of our marketing efforts. These range from small firms specializing in superconductivity such as Conductus; Superconducting Technology Inc. ; and companies specializing in conductive polymers such as Eeonyx and Uniax; - to large manufacturers such as Lockheed-Martin.

Eeonyx
This firm is actively developing products based on conducting polymers. They have indicated that they believe Ultraconductors can be used to improve a product line they are planning for electromagnetic shielding.

Poly-Plus Battery Co.
Poly-Plus is developing what is perhaps the most practical lithium polymer battery in the world for mass produced electric and hybrid electric cars. The technology originated at the Lawrence Berkeley Laboratory operated by the University of California. Poly Plus has been developing a commercial version of this lithium polymer battery for the past four years. This battery may be substantially improved by our materials.

Trojan Battery Co.
Trojan is one of the most experienced and also among the largest manufacturers of deep-discharge lead-acid batteries in the world. They are developing an advanced bipolar lead-acid battery for near-term application to electric vehicles of all types.
This product may be substantially improved by our materials.

Pinnacle Research Institute
Pinnacle is developing both ultracapacitors and bi-polar lead acid batteries. They have had substantial government support and are allied with major automobile companies with regard to advanced development of both systems for electric and hybrid-electric cars.
These products may be substantially improved by our materials.

Maxwell Laboratories
Maxwell has a distinguished reputation in the manufacture of specialized capacitors. They are developing an advanced ultracapacitor with government support. High voltage variations of these units may be substantially improved by our materials.

Electro-Energy
Electro-Energy is developing the most cost-effective variation of the NiMH battery system we are aware of for electric vehicles. They have strong NASA support and have been very interested in using the Ultraconductors for intercell connections.

CONCLUSION

The project set out to find feasible applications for the Ultraconductor technology. It was found that there are both long term and short term applications.

The short term applications were not envisioned when the proposal was written, so the greatest success of the project has been discovering these military and commercial applications, described in the phase II proposal.

The long term applications which are exciting are those that were shown in the project to be feasible when wire is achieved. This not only includes cables but also short term magnetic energy storage, even if the wire is not a superconductor.

The applications that depend on the polymer being a superconductor cannot be assessed presently, but there are now some proposed experiments to explore this further.

The economics of production of the material would appear to parallel that of semiconductors - the raw material is inexpensive, but the processing will probably have to be in a clean room to improve the yield, and yield will govern cost. As with semiconductors, the costs will be reasonable in volume, ensuring a large market.

APPENDICES

A. SINGLE POINT TEST SET
B. MULTIPOINT TEST SET
C. POLYMER FILM SAMPLES - A DESCRIPTION
D. PROBE DESIGN
E. AFM SCAN
F. PHASE II PROPOSAL SUMMARY

TEST SET OVERVIEW

The "Single Channel" test set is designed to be used with a small diameter probe (less than 1 mm) to show conduction in one or more channels. Single channels, after training can handle 10 A to 50 A or more.

The "Multichannel" test set is designed to be used with a large (1 cm diameter) electrode, and to be able to supply a high current pulse. With a single sample, a current of up to 2000 A may be demonstrated. It is also possible to use 2 samples of Ultraconductor on copper discs - put them touching polymer to polymer and passed a pulse of up to 1700 amps, without damage.

First polish the copper substrates to make good contact. They are sandwiched between copper striplines to carry the pulse with low inductance. The pulse comes from a 0.05 microfarad, low inductance capacitor, charged to 3000 volts, switched by a "triggered gap" switch (a vacuum device), or a manual press contact. The current is measured through a 5 milliohm low inductance resistor using a digital storage oscilloscope.

APPENDIX A - SINGLE POINT TEST SET

This Test set is to enable the individual conducting points to be examined under a microscope and to provide controlled current pulses at that point. The set provides 5 microsecond wide pulses, when the button is pushed. The probe is set up to swing out of the way for microscope viewing.

Single-point polymer test set procedure:

I. To set up for viewing probe contact point under microscope:

Place an uncoated coin or foil under probe with a small piece of paper attached. Coin or foil must be held in position, to provide correct thickness.

Using the gold pin probe, rub the tip with pencil lead, then press the probe into the paper to leave a mark. (Clean the tip after doing this.)

Put test set on microscope stage with means for positioning set under objective. Move test set using positioning means until dot is centered in field. If possible, lock positioning device at this position. The test set is then removed from the microscope stage.

II. Find conducting point on polymer:

Connect multimeter to test set with one lead to ground plane (point A), the other to the test-probe end of the 1 ohm resistor (point B).

Set multimeter to lowest resistance range. With a small amount of weight on probe (3-5 gm - a few small washers or nuts over upper end of probe), lower probe gently onto polymer sample. Wait a few seconds to see if point will conduct. Moving probe slightly or varying pressure gently may aid in finding conducting point.

If low resistance conduction (< 0.2 ohms) is not found, raise probe, move sample slightly, and repeat this procedure.

III Pre-Test Examination

When a point is found that conducts well, disconnect leads, swing probe arm back (sample must be held firmly in place), and place test set in position on microscope stage. Examine point of contact to ensure point of probe contact is undamaged. Note any marks in area of contact (pre-test examination).

IV. Current pulse test:

Remove test set from microscope stage and lower probe onto sample. Add weight if needed to ensure low-resistance conduction.

Connect leads from D.C. power supplies (+5 volts fixed and 0 to +175 volts variable) to terminal strip as labeled.

Connect multimeter in 20 volt range: negative (-) lead to ground (point A: copper surface), positive (+) lead to left end of white capacitor (point C).

Connect oscilloscope probe to anode of diode (point D: between capacitor and 1 ohm resistor). Ground probe to copper surface.

Turn on +5 volt supply and set output of (0-175 volt) variable supply for +4.5 v. Set oscilloscope to capture a negative 1 volt pulse with pulse width of approximately 5 microseconds.

Press button E to trigger pulse. Pulse should be about 1.0 v. peak amplitude and < 5 microseconds wide. If it is considerably larger in either amplitude or width, resistance through sample is excessive. Re-check resistance with multimeter to ensure < 0.2 ohms from test probe through sample to ground.

When pulse appears normal at +4.5 v., increase voltage on variable supply in steps of 2 to 8 volts (use smaller steps at lower voltages). Voltage/current curve should pass through the following approximate points:

4.5 V - 1.0 A
20.2 V - 10.0 A
100.0 V - 59.0 A
162.5 V - 101.0 A

A second oscilloscope probe may be attached to test-probe side of 1 ohm resistor (point B) for differential measurement of pulse amplitude.

V Post-test examination

Before increasing the current to the next step the film should be examined for damage in the microscope.

Note 1: There is a "training" (conditioning) effect, whereby multiple pulses increase the current carrying capability. The samples have not been trained and that is why it is necessary to start with low currents.

Note 2: This is an "R & D" sample! There is no guarantee that a point will carry many amps. We have found most points will carry 10 amps, and some will carry up to 100 amps.

Note 3: You may want to design your own probe to reduce the probability of piercing the polymer film.

The single point test set enables the check out of the Ultraconductor at individual points.

It is not possible to guarantee that there is only one channel under the probe, but the probability increases as the probe area decreases. However, with a small probe area it is important to avoid piercing the film.

The single point test provides a more precise approach for exploring current versus voltage curves, and variation with pressure. If a point is destroyed by excess current the rest of the sample is still good.

The large electrode area in the multipoint test set has the advantage of a lower probability of piercing the film. The disadvantage is that it is easier to damage the whole film, either by friction (scratching) or by excess current.

APPENDIX B - MULTIPOINT TEST SET

Test Set Procedure

The Test Set is designed for high currents. At low currents the switch (manual or triggered gap) is not consistent. The total circuit resistance is only about 100 milliohms, so any resistance in the switch (during the nanoseconds of initial closure) is significant.

In all cases the circuit should be pulsed 10 times to get consistency and an average result.

At higher voltages the manual switch undoubtedly strikes an arc (in the switch) which persists for the duration of the oscillation.

At lower voltages the switch may not arc over and may make initial contact at just one microscopic point (resistive) and is more likely to exhibit "bounce", and inconsistency.

Training

The normal sequence is to pulse at 50, 100, 250, 500 and 1000 input volts.
At each voltage it is pulsed once and then the sample examined for any damage. Then the sample is pulsed 9 more times at that voltage.

Difference between Ultraconductor polymer on copper foil and a plain copper foil:

At high voltages, no measurable difference is expected.

At low voltages:

If differences are a consistent result, the following are possible causes-

1) In the setup, if there is a larger loop in the copper foil this could introduce more inductance

2) The Ultraconductor has tunneling at the electrode and the substrate (this varies with pressure), which will appear as a resistive element, and be more dominant at lower V-I because of the shape of the V-I curve for tunneling.

3) It is not known how many channels are active in parallel for a current pulse. The fewer the channels, the higher will be the inductance of the sample. For example if it were only one 1 micron channel, this would be a large discontinuity in the current path which is otherwise over 1 cm wide.

4) Since the current must flow from the electrode to each channel, this constriction of the current within the electrode creates greater electrode resistance.

5) Due to the tunneling and current constriction described in 2) and 4) the voltage profile across the sample may vary more at larger currents. This greater voltage may create current flow in channels which would otherwise not conduct. Another way of expressing this is to assume that channels start conducting over a range of voltages (microvolts to volts) depending on how far beneath the surface is the superpolaron. Hence the first channels to conduct - at the lowest voltage - act like diode limiters on the voltage, and the voltage does not turn on the channels with a higher threshold. By pulsing 1000 amps or more, it is assumed that more channels are active.

The more channels the lower the inductance and the resistive components (tunneling and constriction).

APPENDIX C
POLYMER FILM SAMPLES - A DESCRIPTION

All samples available are of a silicon based polymer. It is recommended that you first probe the samples to determine the existence and number of conducting regions. You may use a standard ohmmeter, but with a rounded tip to avoid piercing the film. The ohmmeter may read as high as several ohms, depending on the individual channel and the pressure, and the history of current through the channel. The resistance appears to be caused by the tunnelling between the electrode and the film - it does not vary with film thickness.

Initially, when the conductive channels are first formed, the polymer can take a few ma per channel - up to a 100 ma pulse, and must be "trained" to go to higher currents. High current pulses heat the electrode tips, where the current is constricted to the channel diameter - typically 1 micron - hence must be at a low duty cycle, for example 2 microsecond pulses every second (1 -2 Hz).

Polymer film samples
Notes:

1. These samples are polymer films, typically about 10 microns thick, on a metal substrate. The films contains a number of electrically conducting regions. The conductivity is through the film, to the metal substrate, not from point to point on the surface. The rest of the surface is a normal dielectric insulator.

2. Use a current limited system (100 milliamps max).

3. The ideal probe is an iridium coated disc, pressed on the surface. A 4 mm probe will typically cover one or more conducting regions.

4. To achieve conduction it is necessary to apply some pressure to the probe, e.g. 200 grams.

5. The thermal conductivity is normal for a 10 micron thick polymer; that is, it is basically a thermal insulator.

6. Please use tweezers to handle. The typical sample is on a copper disc. Note the half-moon near the edge - this is where it was held when being coated, and is the best place to grasp the sample.

Please return the samples after testing to MPI (Tel 707-829-9391)

APPENDIX D

PROBE DESIGN

APPENDIX E - AFM SCAN #1 By Digital Instruments

APPENDIX F - PHASE II PROPOSAL SUMMARY

Abstract.