58916-00-105

ANL/CP--74584

DE92 004148

DEC 1 3 1991

SELF-RECOVERING SUPERCONDUCTING STRIP DETECTORS*

A. Gabutti,** and K.E. Gray

Materials Science Division
Argonne National Laboratory, Argonne, Illinois 60439

IV International Workshop on Low Temperature Detectors and Dark Matter, Oxford, UK, September 4-7, 1991

jmc

*This work was supported by the U.S. Department of Energy, Division of High Energy Physics and Basic Energy Sciences-Materials Sciences under contract #W-31-109-ENG-38.

**Present address: Laboratorium fur Hochenergiephysik, Universitat Bern., CH 3012 Bern Switzerland

Self-Recovering Superconducting Strip Detectors.

A. Gabutti*, K.E. Gray
Argonne National Laboratory, Argonne IL 60439

Abstract

Using a 1.8 μm wide superconducting strip made of granular tungsten, we have observed self-recovering pulses when the detector is irradiated with a ^{55}Fe 6 keV X-rays source. For low values of the bias current (i.e. I_b<30μA at T_b=1.5K) the superconducting state is recovered in 10-50 ns giving voltage pulses across the strip of few hundred μV in amplitude. At high bias currents the detector did not self-recover and a constant counting efficiency was measured at different operating temperatures. There are good indications that this high counting rate can be extended to all the reduced bias currents where the detector is able to reset itself after every switch. The current threshold between collapsing and propagating switches and the time evolution of the voltage pulses can be described using a thermal propagation model developed in previous works. The ability of detectors to automatically recover the superconducting state in a short period of time after sensing a particle is encouraging in the feasibility study of fast superconducting microvertex detectors and also confirm the potential application of superconducting strips as high fast resolution X-rays detectors.

*Present address: Laboratorium für Hochenergiephysik
Universität Bern. CH 3012 Bern. Switzerland

1. Introduction

Detectors based on observing superconducting to normal transitions caused by the passage of high-energy charged particles through thin-film strips have been recently studied as possible candidates in the realization of high-resolution tracking detectors for high-energy physics experiments [1,2,3]. The detector works as a thermal switch, detecting the passage of the particle switching from the superconducting (off) to the normal state (on). The strip is immersed in a liquid helium bath of temperature $T_b<T_c$; the sample is in equilibrium with the bath temperature and a bias current $I_b<I_c$ flows into the strip. The energy loss by a charged particle passing through the strip, drives a small volume of the superconducting film above the critical temperature creating a normal hotspot that propagates in the surrounding superconducting film.

The difference in specific heat between the superconducting and the normal state plus the amount of ionizing energy deposited by the interacting particle are responsible for the maximum size of this normal hotspot [4]. To sign the passage of the charged particle, the full strip cross section has to be driven normal during the switching process to develop a voltage across the strip. This resistive region can grow increasing the amplitude of the detection voltage (i.e. propagating regime) or it can collapse in a nano second time scale (i.e. self-recovering regime) depending on the balance between the heat dissipated in the normal region and the heat flowing in the surrounding superconducting material.

Using a 1.8 μm wide, 0.24 μm thick and 550 μm long superconducting strip made of granular tungsten (T_c=2.16 K) we have observed such behavior detecting propagating pulses for high bias current and collapsing signals with amplitude of ~200 μV and recovery times ~50 ns for low bias currents [5]. In the propagating regime a plateau in the counting efficiency versus bias current was measured for a wide range of operating temperatures.

2. Granular Tungsten Strips

Superconducting strip detectors require only a two steps fabrication process: films are deposited on electrically insulating substrates by sputtering or electron beam evaporation and the detector geometry is patterned using a photolithographic process. In a practical detector the strips have width of 0.5-2 μm and the same superconducting film can be used for the strip as well for the voltage and current leads. The only interaction between strips is via the heat propagation in the substrate and since the temperature of the particle-heated region will decrease with its expansion from the impact point, we can estimate that it is possible to avoid thermal interaction between strips whose length scale is > 1 μm. The absence of complicated multistep photolithographic process plus the tested excellent radiation hardness of superconducting materials [6], are of great interest in the realization of a microvertex detectors with potentially higher spatial resolution and radiation hardness than present silicon microstrip detectors.

In previous works, tests with soft X rays and beta particles were performed on Nb [3] and granular aluminum (g-Al) [2,7] strips and it was found that the lower T_c of g-Al (1.5-2 K) compared to ~9 K for Nb, led to better performance. This is due to the lower enthalpy which creates a larger normal region for a given energy deposited by the ionizing particle. As a consequence materials with a low T_c (~2 K) were chosen in the detector fabrication. Switching experiments with g-Al strips irradiated with 2.3 MeV beta particles showed that to improve the detection of minimum ionizing particles (mips) materials with high atomic number have to be used. Recent calculations based on a microscopic analysis of mip interaction with thin absorber [8] have shown that the spectrum of the energy lost by the particles is dominated by the plasmon losses. For 1.5 MeV electrons interacting on 0.4 μm of silicon, the mean number of collision has been calculated [9] in only 1.59 and the most probable energy lost ΔE in 16 eV. For thin g-W and g-Al absorber the energy-loss spectrum of mips has not been yet studyed, but it is possible in same extent extrapolate from the data for silicon. In the case of g-Al the main plasmon peak is likewise near 15 eV when for g-W is at 25 eV [9] and for a thin tungsten absorber we can roughly evaluate an energy lost about 10 times bigger than for the same thickness of g-Al. The high number of collisions expected in granular tungsten can narrow the statistical distribution of energy loss improving the detector performance.

In fig 1 the radius of the initial hotspot in g-Al (T_c=2.08 K) and g-W (T_c=2.16 K) for an energy deposition ΔE of 1 keV/μm is plotted ver us the reduced temperature $t=T/T_c$. The radius r_n of the hotspot is evaluated from $\pi r_n^2=\Delta E/\Delta H$ using the energy balance model [4] in the hypothesis of an uniform temperature distribution T_c inside the normal region. In the formula, ΔH (J/cm^3) is the difference in enthalpy between the normal (T_c) and superconducting state and it was calculated using tabulated values for the specific heat [5,7] with the BCS correction for the superconducting state.

In the previous tests with g-Al strips only propagating pulses were detected because the normal state resistivity (~10 μΩcm) of the film was too low to generate detectable self-recovering signals. To improve the detection of collapsing pulses granular tungsten films with normal state resistivity of 620 μΩcm were electron beam evaporated at a pressure of $4x10^{-6}$ torr (2-3 nm/min) over a lift-off mask [10]. The mask design was the same as used previously [5] with chips containing several strips of different widths, each with various voltage leads distributed along its length to isolate possible geometrical defect. The film thickness was 0.24 μm with a critical temperature of 2.16 K and a ratio $\rho_{300K}/\rho_{4.2K}$ of 0.97. The enhancement of T_C in the film respect to the bulk value of 16 mK is correlated with the presence of both β-W phase (A15 structure) and α-phase (bcc structure) and trasmission-electron micrographs showed a fine grained structure with an average diameter of ~4nm in good agreement with literature values [11, 12].

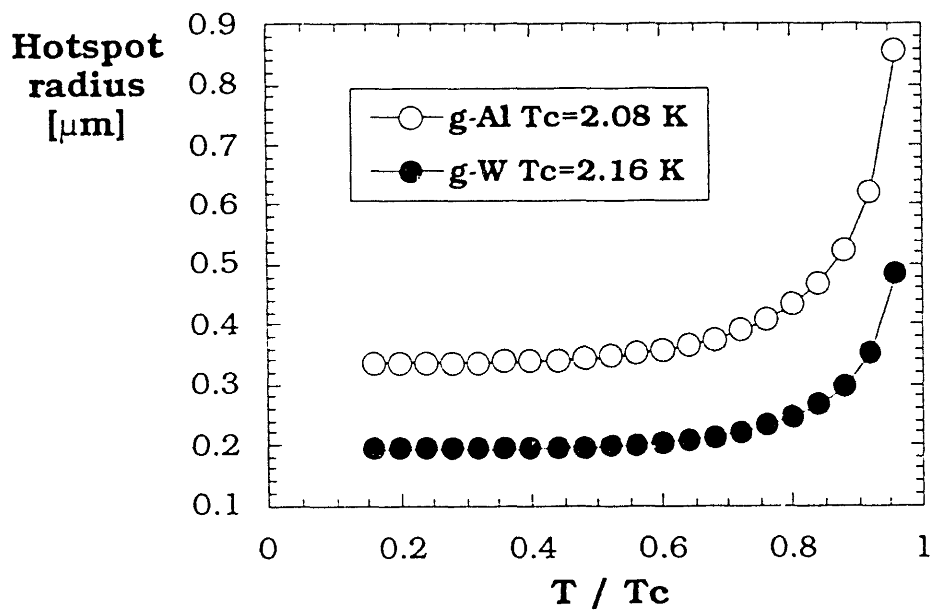


Fig. 1 Calculated hotspot radius for an energy deposition of 1 eV/μm in g-Al and g-W versus the reduced temperature T/T_C.

3. Experimental Results with 6 keV X-rays.

The g-W strip, 1.8 μm wide, 0.24 μm thick and 550μm long was irradiated with 6 keV X-rays which are absorbed in the film by photoelectric effect. A 3.2 keV photoelectron is ejected from the M-shell which has an energy level of ~2.8 keV [13]. The photoelectron is predominantly followed by emission of another, 1.73 keV electron from the Auger MNN transition, since the relative probability for photoluminescence is small [14]. Assuming that the excess energy due to X-rays absorption ΔE= 4.93 keV is deposited in the absorption point, the radius of the initial spherical hotspot calculated from the energy balance model is almost 4 times bigger than the strip thickness [5]. Thus the heat generated in the initial hotspot will easily bridge the strip cross section.

Typical results for counting efficiency of 6 keV X-rays from a ^{55}Fe source are plotted in Fig. 2 as a function of the reduced bias current for five operating temperatures. The detector was mounted in close proximity to the source and was placed in liquid ^{4}He which was pumped to reach the temperature range of 1.3-2.2 K. The temperature of the liquid helium bath was stabilized using a resistance heater controlled in feedback by a thermometer and the measurements at different temperatures were taken sequentially.

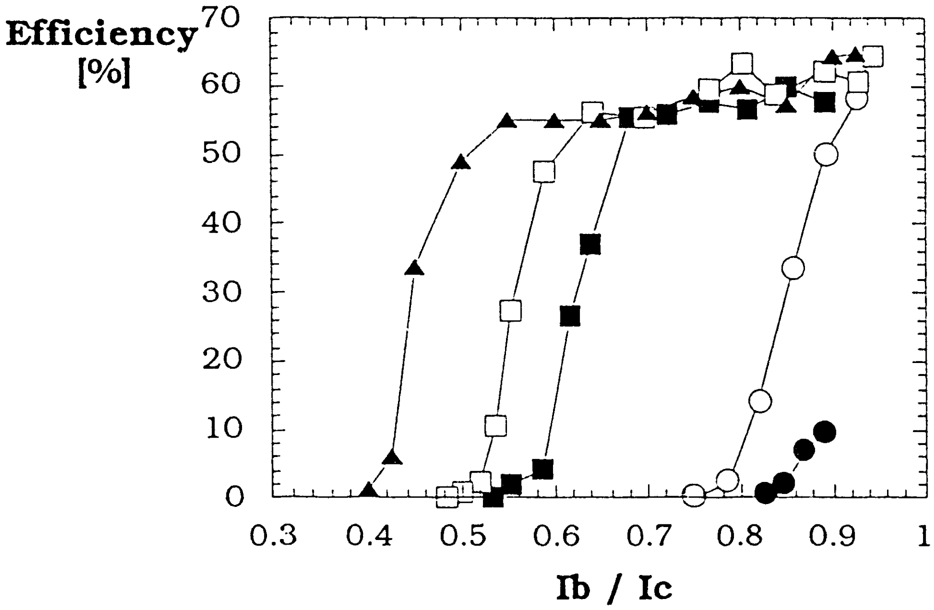


Fig. 2. The counting efficiency of the g-W detector for X-rays, defined as counts divided by calculated x-ray interactions in the film for various temperatures: 1.9 K (solid circles), 1.86 K (open circles), 1.74 K (solid squares), 1.67 K (open squares), 1.5 K (solid triangles).

The measured efficiency in Fig. 2 is only for propagating normal regions. The strip was biased with a square wave current generated by a voltage source controlled by a pulse generator to allow the strip to recover the superconductivity if a propagating switch had occurred. The bias current cycled between a constant fraction of the critical current $I_b < I_c$ for 6 ms and zero for 4 ms with a frequency of 100 Hz which was higher than the expected rate of photon interacting within the active strip volume (~20 Hz). The large voltages associated with propagating hotspots were recorded on a multichannel counter. The efficiencies were obtained by dividing the number of counts recorded in 600 s by the number of X-rays calculated to interact within the active strip volume during the time in which the current was on. The plateau in the efficiency curves in the propagating regime imply that the detector has reached its full intrinsic efficiency although calculations of the expected rate indicated a relative efficiency of only ~60%. Because of the inadequate accuracy in the measured source-to-detector distance and in the determination of the source activity ($\pm$15%) the estimated efficiency has to be considered most likely as a lower limit. The reduced efficiency measured for T_b>1.8 K is due to the presence of both collapsing and propagating pulses.

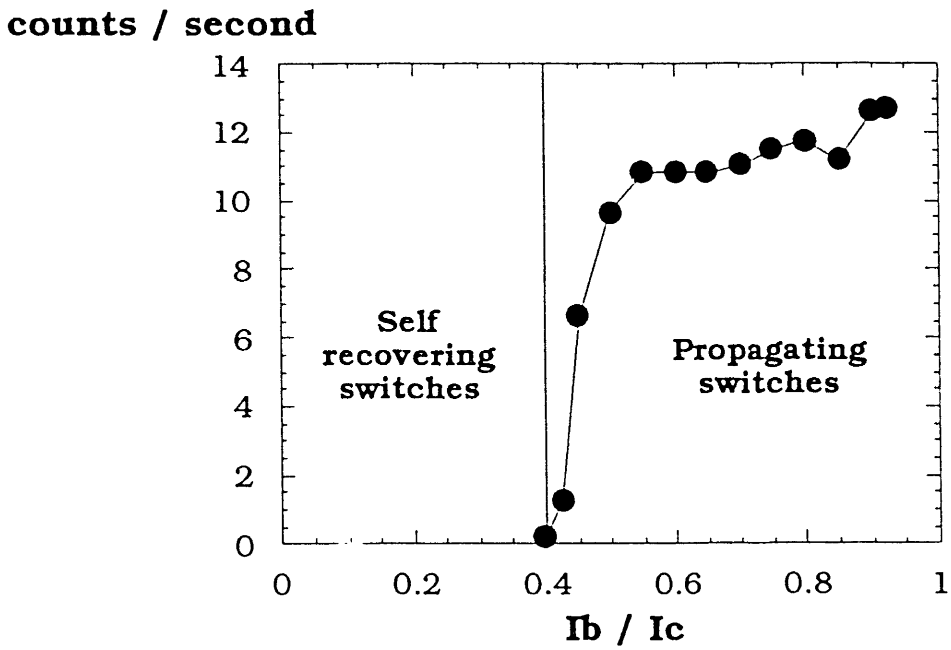
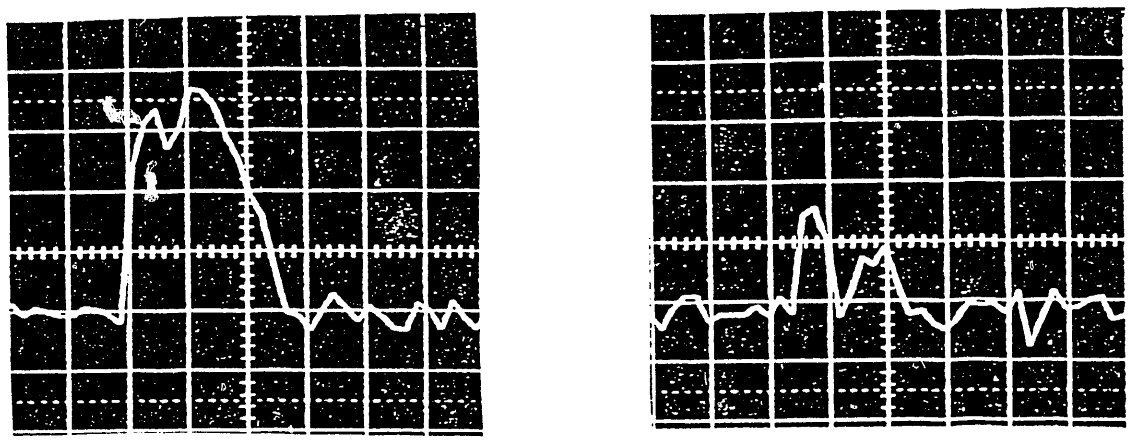


Fig. 3. The counting rate of the g-W detector for X-rays at T_b=1.5 K. The line identify the boundary between propagating and self-recovering switches at I_b=I_{ms}=30 μA.

Collapsing pulses occur for low bias current density and the detector reset itself after every switch. To investigate the self-recovering regime the detector was biased with a constant voltage source and the voltage pulse coming from the particle detection was amplified with a fast linear preamplifier (HP8447A) of band width 400 MHz and gain 40 dB. In Fig. 3 the boundary between propagating and collapsing pulses is shown for the operating temperature of 1.5 K. The curve drops for I_b/I_c<0.4 because collapsing pulses start to appear. For bias currents below the threshold current I_{ms} =30 μA, only collapsing switches were measured. Unfortunately the frequency of the self-recovering switches was not accurately evaluated because the voltage amplitude of the pulses (50-300 μV) was below the threshold used to trigger the counting electronic.

4. Self-recovering pulses.

The thermal propagation threshold between propagating and collapsing normal regions depends on the balance between the power dissipated per unit area in the normal region ($\rho_n J^2 d$) and the heat flowing into the substrate and liquid ^4He. In the case of a particle interaction in a g-W strip the normal region length L_n is less than 1μm and it is shorter than the thermal healing length η~19 μm [5]. The threshold current I_{ms} for propagating switches was calculated in previous works [2,7] assuming that the thermal conduction along the film's length into the superconducting regions surrounding the hotspot dominates over the heat flow into the substrate and ^4He. In this model the threshold current density $J_{ms}=I_{ms}/wd$ (w=1.8 μm, d=0.24 μm) can be determined from $\rho_n J^2_{ms} = 0.5k(T_c-T_b)/L_n^2$ where k is the thermal conductivity of the g-W film (9.6x10^{-5} W/cm K) [5]. The measured I_{ms} are in agreement with the calculated one and for bias currents $I_b < I_{ms}$ only collapsing pulses were observed irradiating the g-W strip with a 6 keV X-rays source.



a) b)

Fig. 4. Collapsing transient responses of the detector to particle-induced switching events at the operating temperature T_b=1.5 K and bias currents: a) I_b=36 μA, b) I_b=29 μA. For both pictures Horizontal 50 ns/div, Vertical 10 mV/div. after an amplification of 40 db. The double structure in the pulses is due to a reflections in the line.

In Fig. 4a,b transient responses of the strip to a particle-induced switching are reported for collapsing normal regions at T_b=1.5 K. The critical current of the strip was I_c=80 μA and the detector was biased at I_b=36 and 29 μA respectively. The double structure in the voltage pulse of Fig 4a,b is most probable due to a reflections along the read-out line since a long (5 m) 70 Ω twinex cable was used to connect the detector to the preamplifier of input impedance 50 Ω.

The reset time after a switch depends on the maximum length L_{max} reached by the normal region before collapsing and on the thermal propagation velocity of the normal-superconducting boundary. The length $L_{max} = (V_{max}\ w\ d)/(I_b\ \rho_n)$ can be evaluated from the maximum amplitude of the voltage transient (V_{max}) assuming that the decay of the bias current I_b, during the fast rise time of the pulse, can be neglected. The measured values of L_{max} are constant for $I_b << I_{ms}$ and show a temperature dependence in agreement with the temperature dependence of the hotspot size [5]. Typical values for L_{max} are 0.8, 0.55 and 0.45 μm at the temperatures of 1.9, 1.74 and 1.5 K respectively.

The constant value of L_{max} are a good indication that the energy deposited by a 6 keV x-ray is able to bridge across the strip by itself. A finite hotspot always appear along the strip independent of I_b and the voltage amplitude of the self-recovering signal depends only on the bias current.

The time for the hotspot to recover depends on the maximum length of the normal region as well as on the negative thermal propagation velocity of the normal-superconducting boundary. Since $L_n << \eta$ it is reasonable assume that the heat flow in the substrate and liquid helium is negligible and the thermal propagation is dominated by the heat diffusion in the superconducting film. For low power dissipated inside the normal region (i.e. $I_b < I_{ms}$) a rough evaluation of the recovering time τ_r can be done using the relation $\tau_r = (L_{max})^2/4D$ where the thermal diffusivity $D = k/C_v$ at T_c is for our g-W sample ~3.7×10^{-2} cm^2/sec. For the pulse of Fig. 4b where $I_b < I_{ms}$ the measured recovering time is in good agreement with the calculated $\tau_r = 13$ ns. At higher bias current (i.e. Fig. 4a) the calculated $\tau_r = 43$ ns is shorter than the measured one, because the contribution of Joule heating $\rho_n J^2 d$ during the recovering time has to be also considered [5].

The inability to count collapsing switches due to limitations in the electronic read-out, prevented us in measuring the detector efficiency in the self-recovering regime. However the presence of a plateau in the efficiency for high bias current and the measurement of a constant length for the collapsing normal region are probably a good indication that the strip efficiency is not effected by the amplitude of the bias current. This imply that the intrinsic efficiency measured for the propagating regime could be extended for all the reduced bias currents also where the detector is able to reset itself after every switch. Further measurements to verify this deduction are in progress.

5. Conclusions

The ability of g-W strips to automatically recover the superconductivity when exposed to a ionizing radiation is an important result for particle detector applications of superconducting strips. The fast self-recovering pulses measured in the granular tungsten strips confirm the potential usefulness of superconducting strips for microvertex detectors as well as for fast, high resolution X-rays detectors. The recovering time of the strip is not yet adequate for the high repetition rate prospected in the next generation of collider (i.e. SSC) but it is an important step in the study of the feasibility of a microvertex superconducting detector.

Faster switches could be obtained with an appropriate choice of the superconducting material to have high normal state resistivity and low critical current to allow the occurrence of detectable collapsing pulses. Tungsten strips could also perform better than previous g-Al samples in the detection of minimum ionizing particles because the high electrons density in tungsten is expected to increase the amount of ionizing energy deposited by the particle.

Acknowledgements

The authors thank G.M. Pugh and R. Tiberio (National Nanofabrication Facility, Ithaca, NY) for helping in the detector fabrication, Dean Miller (Argonne National Laboratory) for the microscopy studies of the g-W film, Klaus Pretzl and Stefan Janos (University of Bern) for useful advices on the presented paper This work was supported by the U.S. Department of Energy, Divisions of High Energy Physics and Basic Energy Sciences-Materials Sciences under contract #W-31-109-ENG-38.

References

[1] R.G. Wagner and K. E. Gray, *Superconductive Particle Detectors*, edited by A. Barone (World Scientific, Singapore, 1988), p. 204.

[2] A. Gabutti, K.E. Gray, R.G. Wagner, and R.H. Ono, *Nucl. Instr. and Meth.*, A289;1,2 (1990) 274

[3] A. Gabutti, R.G. Wagner, K.E. Gray and R.H. Ono, *Nucl. Instr. and Meth.*, A278 (1989) 425.

[4] A. Gabutti, K.E. Gray and R.G. Wagner, *Low Temperature Detectors for Neutrino and Dark Matter III*, edited by E. Fiorini (Edition Frontieres, France, 1989), p.161.

[5] A. Gabutti, K.E. Gray, G.M. Pugh and R. Tiberio submitted to *Nucl. Instr. and Meth. A*

[6] P. Grebshammer, H.W. Weber, R.T. Kampwirth and K.E. Gray, *J. Appl. Phys.* 64 (1988) 1301.

[7] A. Gabutti, K.E. Gray, G.M. Pugh and R. Tiberio, *Nucl. Instr. and Meth.*, A306 (1991) 220.

[8] H. Bichsel, *Nucl. Instr. and Meth.*, A00 (1990)

[9] H. Bichsel, private comunications

[10] the detectors were patterned by G.M. Pugh and R. Tiberio at National Nanofabrication Facility, Ithaca NY

[11] K.L. Chopra, *Phys. Lett.* 25A (1967) 451

[12] O.F. Kammerer and M. Strongin, *Phys. Lett.* 17 (1965) 224

[13] W.H. McMaster, N. Kerr Del Grande, J.H. Mallett and J.H. Hubbell, *Compilation of X-Ray Cross Sections*, LRL Report

[14] L.E. Davis, N.C. MacDonald, P.W. Palmberg, G.E. Riach and R.E. Weber, *Handbook of Auger Electron Spectroscopy*, (Physical Electronics Ind., Inc., Eden Prairie, Minnesota, 1976), p. 45.

[15] K. E. Gray, R. T. Kampwirth, J. F. Zasadzinski and S. P. Ducharme, *J. Phys. F: Met. Phys.*, 13 (1983) 405.

END

DATE
FILMED
01/30/92

I