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Final Technical Report

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ADVANCED COMPONENTS FOR SPACEBORNE INFRARED ASTRONOMY

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SUMMARY

The need has been identified in two separate areas for much improved cryogenic components to be used in future spaceborne infrared astronomy missions such as SIRTF (Shuttle Infrared Telesope Facility) and LDR (Large Deployable Reflector): (1) low noise amplifiers operated at cryogenic temperatures with IR detectors (2) cryogenic actuators and motors which dissipate extremely low amounts of power. This study addressed the feasibility of achieving breakthroughs in both these areas by means of a development effort starting with commercially available devices and materials. Positive recommendations are made in both areas.

Concerning cryogenic amplifiers the study was directed toward the design of a true cryogenic Si JFet which would be optimized for low noise operation at much lower temperatures than are currently possible. It was found that quite significant gains are possible through a development program consisting of a three part application of materials technology involving (1) high purity Si (2) optimum dopants and (3) very high doping levels. Sensitivity of a few electrons/sec at temperatures of 10 to 30 K seem attainable following a straightforward low cost development effort which is outlined in this report. The availability of a true cryogenic JFet would result in important applications with a wide variety of photon counting detectors from optical to far-infrared wavelengths.

In the second area included in this study, the feasibility of a simple stepper motor equipped with superconducting coils to eliminate the normal electrical dissipation at temperatures below 9 K was demonstrated by construction and test of such a device based on a standard commercially available motor. Test data show useful torque at immeasurably low power levels compared with normal operation using copper rather than superconducting coils. Several aspects of the design which require further study were identified. However, it was shown that quite simple designs are likely to lead to a broadly applicable family of components ranging from motors and actuators used in LHe cooled apparatus in space to many different types of earth based cryogenic systems.

INTRODUCTION

This phase 1 study was concentrated in two areas following an initial analysis of the proposed topics. The two areas chosen for further study were: (1) cryogenic amplifiers using silicon JFets (2) superconducting motors and actuators. Both of these technologies are of great importance for future spaceborne infrared astronomy programs where the entire telescope and/or associated instruments must be cooled to very low temperatures. SIRTF (Shuttle Infrared Telescope Facility) and LDR (Large Deployable Reflector) are two examples of future NASA missions which would greatly benefit from progress in both these areas.

The need for improved cryogenic amplifiers for use with IR detectors in space is clearly demonstrated by IRAS (Infrared Astronomy Satellite), Space Lab 2 IRT (Infrared Telescope) and COBE (Cosmic Background Explorer), three recent or current missions which use conventional silicon JFet amplifiers. Both the noise performance and the operating temperature of the devices used in these missions, (the J230, manufactured by Siliconix, Inc. and Infrared Laboratories, Inc.) are higher than required for future missions. This study addresses the possibilities for development of a true cryogenic JFet which would operate at much lower temperatures than available devices and provide improved noise performance.

The need for small motors and actuators to operate at temperatures below 10 K with essentially no power dissipation is apparent when one considers the various mechanical functions which must be performed in a system such as proposed for SIRTF or other space instruments operated at cryogenic temperatures. This study has already demonstrated through tests of a simple model the feasibility of such devices. A small 48 position, reversible stepper motor has been constructed using commercially available superconducting wire, NbTi. The results of tests at 4.2 K are summarized; these results are then used to establish performance goals for future designs and to serve as a guide to future developments and applications in this area.

Although the aplications envisioned for both tne amplifers and motors considered in this study are in connection with future space missions, it is apparent that other applications are possible and may ultimately become quite significant. For example, the cryogenic amplifiers can be used with any type of photon detector where noise levels of a few electrons/second and operating temperatures of 77 K or lower are required--this includes optical and IR detectors of many different types. There may also be other signal processing applications for such devices. Clearly, as the technology of superconducting power transmission is developed the need for mechanical actuators operating at low temperatures will become more widespread.

CRYOGENIC AMPLIFIERS

A. BACKGROUND

Sensitive IR detectors must be cooled to low temperatures with the longer wavelength detectors requiring more cooling. Even at wavelengths as short as 2 microns cooling well below 77 K, LN2, may be advantageous in terms of sensitivity and dark current. Since IR detectors generate free charge or current in proportion to the incident photon flux, the readout amplifier should be able to sense extremely small currents at very high impedance levels. This requires low noise levels--at least a few electrons/second--and operation at or near the temperature of the detector (2 to 10 K). Other requirements are (1) low power dissipation, micro-watts or less, (2) small size, << 1 mm**3, and (3) reliability and ease of handling and testing.

During the development phases of IRAS and Space Lab 2 IRT it became apparent that the Si MosFet amplifier used with LHe cooled IR detectors could not meet all the requirements; it was necessary to develop Si JFet amplifiers as an alternative[1]. COBE now uses the same amplifier module developed for IRAS which was based on the commercially available J230 manufactured by Siliconix. Low has subsequently developed a new type of integrating circuit which also uses a cooled JFet as the amplifier and a MosFet as the reset switch. His recent paper[2] which is attached as an appendix, provides data on both the J230 and the 2N6483. Experience with these commercially manufactured devices, which were designed as low frequency, very low noise amplifiers for use at room temperature, provides the basis for our study of a true cryogenic JFet which will be designed and optimized for low temperature operation.

B. RESULTS OF FEASIBILITY STUDY

(1) OPERATING TEMPERATURE: Low reports that the 2N6483 device manufactured by Intersil is still conducting at 4.2 K whereas the J230 is not. Freeze out of the carriers in the channel has occurred at 4.2 K in the J230 but not in the 2N6483; however, no useful amplification is realized at 4.2K. Both devices use an N-

type channel, probably As, P, or Sb doped. Clearly it is important to use the dopant with the lowest band gap, either P or Sb. It is also important to increase the doping concentration almost to the degenerate level to provide free carriers at as low a temperature as possible. A third consideration is the compensation. At room temperature ordinary semiconductor grade Si which will have minority concentration of several percent, will not show any degradation from these impurities. However, at low temperatures, where both holes and electrons are freezing out, the presence of unwanted traps will reduce lifetimes for the majority carriers as well as their numbers. Thus it is important to use much higher quality raw material for manufacture of a cryogenic device. Fortunately, such material is now readily available.

If all three of these materials aspects are optimized, i.e. (1) lowest band-gap dopant (2) highest feasible concentration of majority dopant and (3) low compensation in the raw material it should be possible to lower the operating temperature quite significantly, from the present range of 60 to 70 K down to the range of 10 to 30 K.

(2) NOISE PERFORMANCE: The noise of a JFet amplifier consists of two major components: (a)) kT noise in the channel impedance, (b) current noise associated with contacts, or surface states. The kT or Nyquist noise is theoretically flat spectrum and is governed by the operating temperature and the dynamic resistance of the output circuit. The current dependant noise is always 1/f type of spectrum and is most significant at low frequencies (for modern

JFets the break point is at about 200 Hz). Since the impedance is the reciprocal of the transconductance the basic noise of the device is reduced by increasing the gain. Thus the same steps that lead to higher gain at lower temperatures will lead to lower impedance and this, coupled with lower values of kT, will produce lower values of noise.

The current dependent term is less predictable but is known to improve with certain processing procedures. Fortunately, much of this work has already been accomplished for us by the designers of the 2N6483 and the J230; this accounts for their excellent performance. It is possible, however, that the contacts can be improved for operation at low temperatures. The same type of ohmic contacts used in cryogenic bolometers will pass the drain current with less noise than conventional sintered Al contacts used on the commercial devices. Thus, it may prove possible to reduce the low frequency noise through better contacts while gaining somewhat at higher frequencies by increasing the transconductance and lowering the temperature.

(3) INPUT CAPACITANCE: The optimum device will have the lowest gate capacitance for a given transconductance. We have concluded that the compromise represented by the design of the 2N6483 is close to optimum. Efforts to improve on this aspect of the design will involve study of the gate junction at low temperatures and the ability to change the mask design used in the manufacturing process. Since the possible gain in performance is modest at best and the cost is likely to be high we do not recommend this area for work until all other efforts

are completed.

SUPERCONDUCTING MOTORS AND ACTUATORS

A. BACKGROUND

Actuators operating at temperatures below 10 K have numerous applications in cryogenically-cooled instruments such as infrared telescopes and spaceborne liquid helium management systems. Stepper motors whose power consumption is small are needed for cryogen control valves and various other drive mechanisms such as filter wheel rotators, beam splitter actuators, and grating changers. The planned Shuttle Infrared Telescope Facility (SIRTF) has applications for a rotating cryogenic beam splitter which feeds the instrument's optical beam to the Multiple Instrument Chamber (MIC) containing up to 6 scientific instruments. Since the amount of cryogen carried into space is usually limited, extremely low power dissipation is required for all types of mechanisms. These low-power actuators can be divided into three general categories. (1) low torque (or force) motors with a precision angular or linear position requirement, (2) high torque, low precision, and (3) high torque, high precision. Good reliability is a necessity for all classes of devices. Superconducting coils along with high-energy permanent magnets show promise for fulfilling the goals of extremely low power dissipation and high force. Linear and angular actuators for Fabry-Perot etalons which utilize NbTi superconducting wire (Airco Superconductors) with CoSm magnets (Hitachi Magnetics) have been built and tested at the University of Arizona by

Nishimura et al[3]. Forces exceeding 5 kg (45 Newtons/Amp) were achieved. With this force applied to an assembly of stiff copper rings, a linear displacement of 80 um was obtained with an accuracy of 0.1 um and an angular tilt of less than 0.3 arcseconds.

B. RESULTS OF FEASIBILITY STUDY

(1) SUPERCONDUCTING STEPPER MOTOR:

A review of available literature revealed several investigations of the properties of stepper motors operated at cryogenic temperatures [4,5]. These investigations concentrated on mechenical properties, especially of the bearings, and on reliability, repeatability, and accuracy. Normal copper wire was used in the coils of these motors, and power dissipation was high.

For the present study, a commercial unipolar 4-phase stepping motor (A.W.Haydon 9904 112 07101 with sleeve bearings) was modified so that two of its four coils were wound with copper-clad NbTi wire. This material becomes superconducting at temperatures below 9 K and is capable of sustaining currents of greater than 10 Amperes in magnetic fields as high as 3 Tesla (3 E 4 gauss). The copper cladding allows adequate thermal conduction within the coils themselves for initial cooling.The motor was mounted in an Infrared Laboratories, Inc. HD-1 liquid helium dewar, and heat-sinking was accomplished utilizing copper straps attached to the cold plate and extending to the areas around the coils. A current-limited 4-phase electronic coil driver was constructed to drive both the normal coil pair and the superconducting coil pair in the proper sequence so that properties of both types of coils could be observed during a single cryogenic run. Table I presents the results of two experiments in which the motor was cooled to 6 K and run continuously for 1 hour delivering a torque of approximately 7 E - 3 Nm (approx. 1 oz-in). The drive signal was varied from 1 step/second to 20 steps/second during the test, and after each continuous run the drive signal was removed and reapplied several times so that the re-start capability could be observed. The motor showed no signs of failure to start or run, either visually through the dewar window, or electrically through a current monitor on the coils.

TABLE I

TEMP (K)	CURRENT (A)	POWER* (W)	POWER** (W)	TORQUE (E-3 Nm)
6	0.100	0.020	0	7.0
6	0.150	0.045	0	10.0
77	0.100	0.067	0.115	7.5
300	0.100	0.560	1.620	7.5

* Copper coil
** Superconducting coil

Since the coil current is directly proportional to the motor's torque, waveforms seen at the current monitor will show any anomalies such as increased bearing friction. Since these waveforms did not change during the tests, we conclude that even the simple sleeve bearings used in the test motor are reliable at cryogenic temperatures.

Optimizing of the motor bearings, e.g. jeweled types similar to those found in mechanical watch balance wheel assemblies, will result in lower friction and could increase reliability. The powdered iron rotor material which was used in the modified commercial motor studied here has not been optimized for cryogenic use. Further research into the properties of materials such as ALNICO-V and CoSm to determine their suitability for cryogenic stepper rotors must be done before the final design of an optimum motor can be determined.

(2) CURRENT LEADS FOR SUPERCONDUCTING ACTUATORS

To deliver the large currents necessary for producing high torques at cryogenic temperatures, electrical leads capable of withstanding the current densities encountered must be attached between the cold coils and the warm dewar outside case. The requirement of low total heat input to the cold area places constraints on the wire size and type of material which can be used. A standard technique to cool these wires is to attach them to a vapor-cooled heat exchanger. Even with this method, the heat conducted through the wires may be a major contributor to the heat load in the cryogenic system. Buyanov, et al[5] have conducted a review of current leads of various designs for use at cryogenic temperatures. Design criteria are given for several types of superconducting lead configurations, and experimental results are given for copper wires. We recommend that further work be done in the general area of leads which carry currents for these superconducting actuators so that heat loads to the cryogenic surfaces can be minimized.

CONCLUSION

1. CRYOGENIC JFET DEVELOPMENT: We conclude that a relatively modest effort, directed toward the materials optimization of standard commercial devices, can produce very significant gains in lower operating temperature and some gain in noise performance. Additional noise improvement may be achievable if better contacts can be used. Other improvements will be more difficult and more costly. We recommend that the 2N6483 be adopted as the starting point for such a program since it is already well optimized in terms of its structue and most of its processing procedures.

The lowest cost approach would involve a number of special runs, using the correct high purity Si and dopants, while systematically increasing the doping level in the channel to experimentally determine the optimum concentration levels. The feasibility of such runs have been established by contacting the manufacturer of the 2N6483.2.

2. SUPERCONDUCTING MOTORS AND ACTUATORS: Through the use of a modified commercial stepper motor cooled to liquid helium temperature, it has been demonstrated that superconducting coils can dramatically reduce power dissipation to the cryogenic cooling system. The wire type chosen for this demonstration model is not necessarily optimum for all applications involving electromagnetic actuators operated at cryogenic temperatures, and it is likely that a development effort will result in improved

devise characteristics. Although the powdered iron rotor utilized in the model resulted in a useful amount of torque, much higher torques at lower applied coil currents will result from the use of high energy density materials such as CoSm. With a higher force or torque available, smaller coil currents can be used resulting in smaller lead wires and thus a reduced heat load to the cryogen.

A research and development effort is clearly indicated which will address the areas of coils, magnetic core and rotor materials, and bearings for rotary actuators. When the positive results of this feasibility study and demonstration of superconducting stepper motors are combined with the results published by Nishimura, et al [3] on superconducting linear and rotatory actuators it is apparent that with further work to optimize the design of the three devices it will be possible to manufacture them in the form of inexpensive products suited to a variety of practical applications. It also appears that most, if not all, of the needs for rotatory and linear motors in systems such as SIRTF can be satisfied by designs based on this work.

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APPENDIX A

INTEGRATING AMPLIFIERS USING COOLED JFETS

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Conventional amplifiers using cooled JFETs have found wide-spread use as readout devices for a variety of infrared detectors because of their low-noise and excellent dc stability. Perhaps the most significant application is in the Infrared Astronomical Satellite (IRAS) focal plane where 62 pairs of J230 JFETs are used in the transimpedance amplifier (TIA) circuit and configuration described by Low[1]. Each individual pair of matched JFETs is mounted, along with a heater resistor, on a suspension of dacron threads inside a photon-tight enclosure so that the device dissipation maintains the correct operating temperature of about 65 K even though the remainder of the focal plane is at 2.8 K. The limiting noise in this case is generated by the 2×10^{10} ohm feedback resistor at 2.5 K, 1×10^{-16} amp/root Hz. Measurements with much larger values of feedback resistance show that about one order of magnitude reduction in current noise can be realized with this circuit at the expense of two orders of magnitude reduction in response time. Therefore, experiments have been undertaken to develop a current integrating amplifier using an electronically operated switch to discharge the accumulated charge. Similar circuits have been used, with a variety of different reset switches, to read the charge deposited in solid state particle detectors (see for example, Boulding[2]). The purpose of this note is to show how a simple integrating amplifier based on commercially available JFETS and MOSFET switches can be used to measure photocurrents from detectors with noise levels as low as 1.6×10^{-18} amp/root Hz (10 electrons/sec.)

The basic circuit is shown in Figure 1 along with the waveform at the output. The readout is completely non-destructive and reset noise does not contribute since sampling of the accumulated charge occurs between resets which are required only when the stored charge has reached a very high level; depending on detector parameters and linearity requirements storage capacity ranges from 1×10^{6} to 1×10^{9} electrons.

Figure 2 shows data taken with a Si:Sb detector operated at 24 microns. The performance of this detector, fabricated at the University of Arizona for use in the Space Lab 2 Infrared Telescope, is documented by Young et al.[3] Table 2 summarizes the parameters of the test and the results. The measured responsivity, R, agrees well with the value obtained by Young et al.[3] in the TIA circuit. It is apparent from these data that extremely low values of NEP can be obtained for integration times of 1 sec and that longer integrations continue to improve the S/N at a rate faster than the square root of time when background noise is not present. The gate capacitance of the 2N6483 JFET was measured by inducing charge onto the gate through a small (1 pf) capacitor in a separate test with the detector and MOSFET removed. This test also gives a limit of > 1 E 15 ohms for the resistive component of the 2N6483 input impedance. Drift rates of 1 to 10 microvolt/sec, independant of charge stored on the gate, are typical and are easily calibrated out along with dark current from the detector. Any detector with low enough dark current, either photoconductive or photovoltaic, will function well in this circuit; excellent results have been obtained with ordinary Si PIN photo-diodes at 77 K and tests are in progress at 100 um with Ge:Ga photoconductors.

Both shorted and open-circuit noise have been measured for a variety of J230 and 2N6483 devices at 77 K. Table 2 summarizes these results and shows that the two types of device are capable of comparable performance under certain circumstances. Tests at reduced temperature show that the 2N6483 conducts current at 4 K when its gate is near ground, greatly simplifing its use in self-heated applications (in effect, the reference side of the matched pair acts as a heater to initiate operation at 4 K. The low power required by the 2N6483, 10 microwatt vs 80 microwatt, and its lower operating temperature, 50 K versus 65 K, are also important advantages.

In conclusion, it is apparent that in very low background applications, where photon rates down to a few/sec are to be measured, the simplicity and sensitivity of the cooled JFET integrator offers great advantages over alternative methods of read-out. It should also be possible to develop Si JFETs with improved noise, lower input capacitance and lower operating temperatures by optimizing the choice of dopants and their concentrations.

This work was supported by the National Aeronautics and Space Administration. Discussions with a number of colleagues have contributed to this work, especially Erick Young.

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Table 1. Test results with 2.5 x 2.5 mm Si:Sb detector at 4.2 K

Condition	(a)	(b)	(c)
dv/dt (μv/sec)	1.74	1480	480
I (a)	1.74 E -17*	1.48 E - 14	4.8 E - 15
P (w)	0	1.38 E - 14	5.0 E - 15
R (a/w)	-	1.07	0.96
I_n (a/Hz$^{1/2}$)	1.5 E - 18	-	-
NEP (w/Hz$^{1/2}$)	1.5 E - 18	-	-

* Dark current, roughly proportional to bias voltage

Table 2. Performance of J230 vs 2N6483 at 77 K.

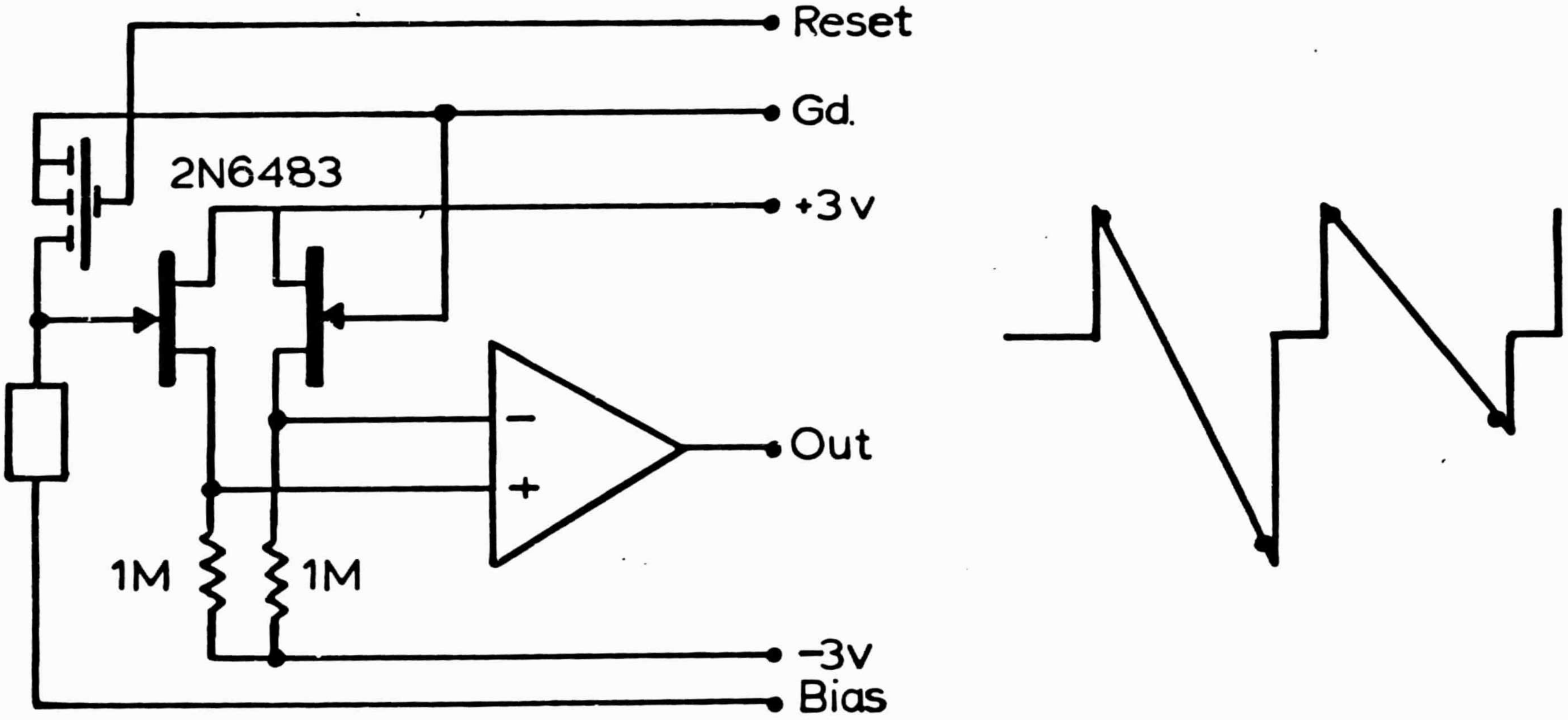
	J230			2N6483		
V(drain)	3.0 v			3.0 v		
V(source)	1.0 v			1.4 v		
I(drain)	40 µa			4 µa		
C(gate)	3 pf			11 pf		
Vn(shorted)*	60	20	10	60	10	4
V_n (open)*	350	40	20	120	25	6

* Spot noise in nanovolt/Hz$^{1/2}$ at 1,10 and 100 Hz.

FIGURE CAPTIONS

Figure 1. The basic integrating JFET circuit with a p channel enhancement mode MOSFET reset switch and a Si:Sb photoconductor. The indicated waveform shows the reset followed by the linear ramp corresponding to both strong and weak signal conditions. The 2N6483 must be between 50 and 80 K; the MOSFET may be cooled to 4 K.

Figure 2. Strip chart records of a test with an Si:Sb detector under three conditions: (a) cold shutter closed, no IR photons present, (b) shutter open, BB source at 773 K, (c) shutter open, BB source at 295 K. Bias voltage = 4.0 volt; bandwidth 0 to 4 Hz; $I = (1 \times 10^{-11})dv/dt$.



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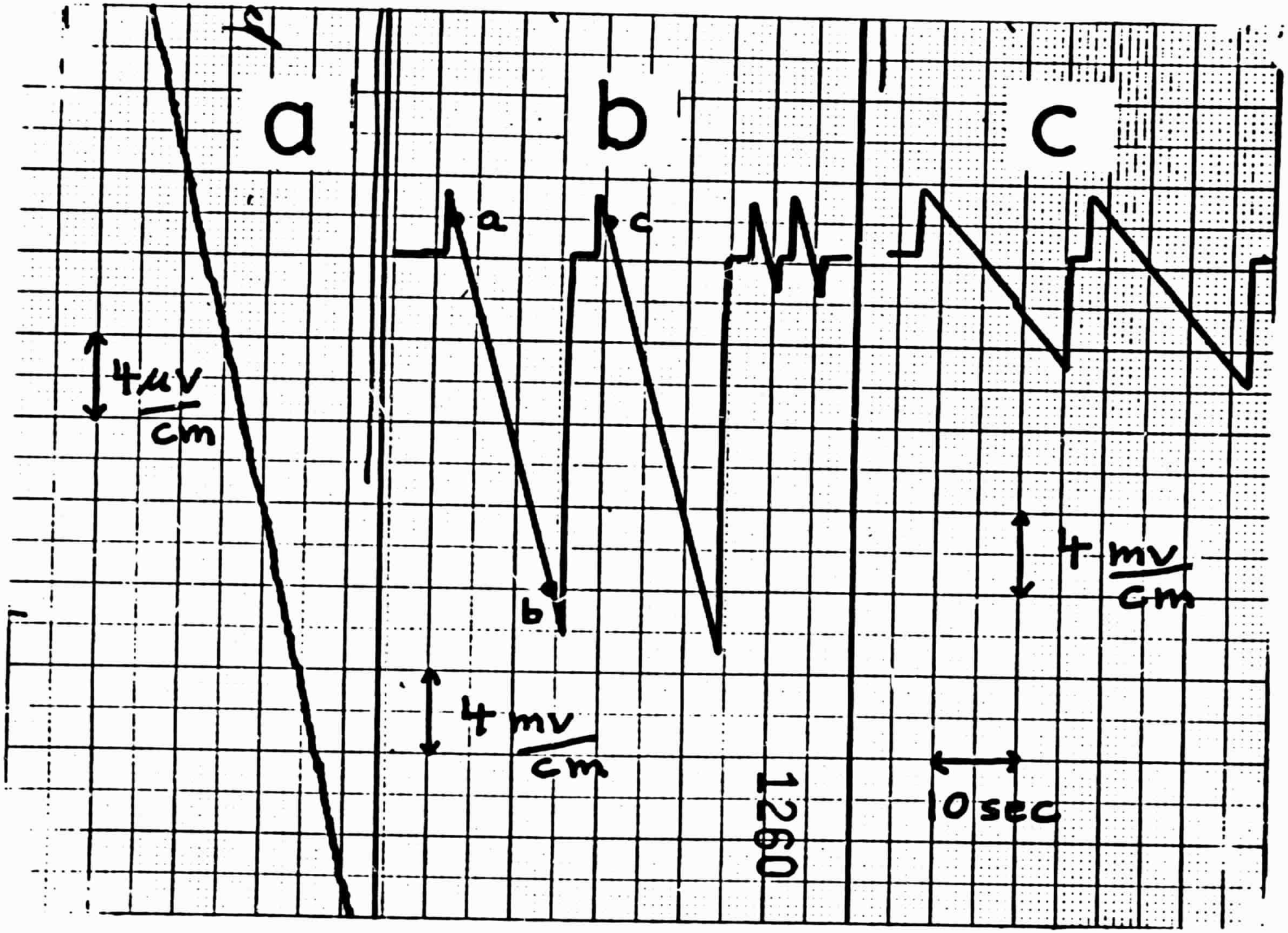

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