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ABSTRACT

A pair of unguarded metal-oxide-semiconductor field-effect transistors has been used to measure ionization-chamber currents in the range 10^{-15} to 10^{-8} ampere. A portable instrument has been constructed which has an input leakage current less than 10^{-16} ampere. It exhibits a high degree of stability, circuit simplicity, ruggedness, low drift, and 0.7-mA drain, which will permit continuous operation for several months. Also, guarded MOS devices, investigated for this application, have been found to have leakage currents in the region of 10^{-18} ampere.

INTRODUCTION

This paper discusses use of an enhancement-mode metal-oxide-semiconductor (MOS) as the sensing element in the measurement of direct currents produced by ionizing radiation in an electrically polarized chamber. These measurements are important in the study of natural radioactivity, fallout, and the activity associated with various charged-particle accelerators and x-ray generators. The earlier electrometers such as the gold leaf, capillary, quartz thread, string, and quadrant have, for the most part, given way to vacuum-tube and vibrating-capacitor electrometers. Vacuum-tube electrometers used in portable equipment typically exhibit grid leakage currents of 10^{-14} to 10^{-15} A. Well-designed vibrating capacitor units have drift rates corresponding to 10^{-17} to 10^{-18} A. The vibrating capacitor units are very stable, but are also very expensive, and generally have input capacities several times as large as either vacuum-tube electrometers or the MOS electrometer described in this article.

MOS TRANSISTORS

Figure 1 is a simplified sketch showing the basic construction of the MOS. As far as its electrometer application is concerned, it differs from conventional field-effect transistors (FET) principally in that its high-input impedance is dependent on the insulating properties of a thin SiO_2 layer between the input gate and other device elements, rather than on the resistance of a reverse-biased p-n junction. Also, unlike the p-n junction FET, the MOS can operate with forward bias in order to enhance conduction without increasing input current, thus "enhancement mode." The source-drain spacing is a few microns wide and a few hundred microns long, and the SiO_2 layer is about 0.1 μ thick. For zero gate-source voltage (V_{GS}), the source-drain junction is reverse biased and only a few nanoamperes flow into the load, R_d. When the gate is biased sufficiently negative with respect to the source, an inversion layer is formed beneath the gate because of the electrostatic repulsion of the electron carriers and the attraction of holes. In this way a p-type layer, or p-channel, is formed between the source and drain. The conductivity of this low-impedance layer is modulated by the gate potential. The threshold V_{GST} for the formation of the inversion layer is about -5 V.

RADIATION DETECTOR

The instrument (Fig. 2) measures the amount of ionizing radiation from such sources as radioisotopes, x-ray generators, charged-particle accelerators, and natural background.

Ionization-chamber current is measured by either of two methods: (a) IR drop (rate-meter function) or (b) time rate of change of charge (integration function). In the integration mode, an input current is not required to maintain a meter deflection. The only input current flow (neglecting the leakage component) is that necessary to charge the electrostatic input capacitance. Because power is not being consumed at the input, the integration function serves as a method of deferring measurement until a large number of charges has been collected. This serves also to smooth out the statistical fluctuations associated with measurement of very small currents. The integration function is particularly useful for low-level background measurements and for measurements made in pulsed radiation fields in which sufficient time exists between pulses to allow each pulse to be analyzed separately. Under these conditions, the rate-meter function would be useless because only the pulse-repetition rate of the field would be indicated. The rate-meter function is best used to measure radiation from nonpulsed sources, such as radioactive isotopes. Rate-meter ranges of 1, 10, and 100 milliroentgens per hour, 1 and 10 roentgens per hour, and integration ranges of 1 and 10 microroentgens per full scale are used.

CURRENT LEVELS

The ionization chamber has a volume of 3700 cc and is filled with one atmosphere of air. A background-radiation field of 10 μR/h produces an ion-chamber current of 3.4×10^{-15}A and requires an integration time of 6 min for a full-scale deflection on the 1-μR range. The MOS X-1004, used as the input sensing device (Fig. 3), showed leakage currents ranging from 2×10^{-16} A to 5×10^{-17}A. Values close to the latter were obtained after the device had been operating for a few hours.

Current in the ionization chamber (corresponding to full-scale deflection) on the 1 mR/h range is 3.4×10^{-13}A. This sets the limit on the value of the largest input resistor at 10^{12} ohms. Handling, shielding, and humidity considerations therefore are not severe. With an input capacitance of 11 pF (8 pF for the device), the longest time constant is 11 sec.

ION-CHAMBER CONSTRUCTION

The ion chamber (Fig. 4), constructed from 1/8-in. Lucite, was thinly coated inside with colloidal carbon and outside with silver paint. The chamber cathode is connected to -300 V and the outer wall is grounded. A sapphire rod 1/16 in. in diam by 1/4 in. long supports the 40- mil anode wire at one end of the gate lea supports it at the other end. Although there has been no evidence of leakage across the sapphire insulator, it would be a worthwhile precaution to have the insulator guarded.

CIRCUITRY

The single-ended differential-amplifier configuration (Fig. 4) obviates the need for quiescent-current bucking, and reduces drifting due to temperature fluctuations. At room temperature the zero drift is less than 1% per day. The instrument has not been temperature cycled. However, because MOS devices are operated by majority carriers, the transconductance should not be a strong function of temperature. (See characteristic curves, Fig. 5). Because the transconductance of the X-1004 is about 600 μmhos in this circuit, further amplification is unnecessary. Typical pentode-connected electrometer tubes have transconductances of only about 10 μmhos. Triode-connected electrometer tubes have transconductances an order of magnitude or more larger, but the grid current is correspondingly greater. Together Q_1 and Q_2 draw 0.7 mA, so that if the instrument were to operate continuously, the 3600 mA-h mercury battery would last about 7 months.

OPERATION OF THE SYSTEM

In the integration function, Switch B(Fig. 4) is connected to the drain of Q_1. Switch A contacts the gate. Both the gate (anode) and Switch A are heavily gold-plated to assure good contact. In this position, the zero is set. Switch A is then lifted off the gate, which rises to a potential proportional to the number of electrons it collects in the ion chamber. The time required for full-scale meter deflection is then used to compute the ion-chamber current, which is proportional to the intensity of the radiation field.

$$I = C\, dE/dt,$$

$$\frac{R}{h} = \frac{I(\mathrm{A}) \times 3 \times 10^{9}\ (\mathrm{esu/coulomb}) \times 3.6 \times 10^{3}(\mathrm{sec/h}) \times T(°\mathrm{K}) \times 760\ (\mathrm{mm\ Hg})}{V\ (\mathrm{cm}^{3}) \times 273(°\mathrm{K}) \times p(\mathrm{mm\ Hg})}\ .$$

In the rate function, ion-chamber current flows through a high-megohm resistor connected between the gate and drain of Q_1. The IR drop produces a voltage at the input proportional to ionization-chamber current.

The maximum sensitivity of the circuit, with the meter series resistance removed, is 5 mV/μA referred to the input.

ION-CHAMBER-COLLECTION POTENTIAL

Figure 6 shows the effect of ionization-chamber-collection potential on the collection efficiency. Measurements of extraneous radiation in pulsed fields, such as those associated with the Bevatron, may indicate only a few μR/pulse. Although this may not seem to place great demands on the collected potential, in reality it does, because these short radiation bursts may have instantaneous rates of 1 R/h or more. Under these conditions, measurements may be in error owing to recombination in the ionization chamber unless a collection potential near 300 V is used.

GUARDED MOS STRUCTURES

Gate-Leakage Current

The source lead of the X-1004 is internally connected to the case of the device. This places the case several volts positive with respect to the gate. Where it emerges from the encapsulating glass the gate lead is physically close to the case. To prevent gate-to-case leakage, the MOS 1009 was fabricated with a floating case. Short-term measurements of gate-current leakage on these devices show that if the case is maintained at a voltage near that of the gate, then the effective gate current can be held near 10^{-18} A.

Guarded MOS Electrometer Ionization Chamber

If the 1009's were to be used in the instrument described, along with a 0- to 20-μA meter of 2100 ohms internal impedance (such as the Weston 1941-T) and drain resistors of 5000 ohms, the sensitivity would be about 5 mV/μA. The input capacity of the 1009 is 1.5 pF, and together with the capacity of same ionization chamber would total 4.5 pF. Because the input capacity would be reduced by 11/4.5, the ionization-chamber volume could be reduced proportionally to 1500 cc without increasing the time required to integrate a given charge. This is so because of the relationship $\Delta t = C\Delta E/I$, which shows that the time Δt required to integrate a given current I is proportional to the product of the input capacity C and the full-scale voltage ΔE. The ionization-chamber current is also reduced by 11/4.5, so that a 10-μR/h radiation field would cause a current of 1.4×10^{-15} A to flow. A further reduction in chamber volume is possible, since the noise or leakage current is near 10^{-18} A. However, it would be desirable to incorporate some amplification in the systems, so that the integration time would not be unreasonably long. For instance, if the chamber volume were to be reduced from 1500 cc to 300 cc, the integration time for a full-scale meter deflection would be five times as long, unless the sensitivity were also increased by the same factor. This can easily be accomplished, as suggested in Fig. 7, by use of a current amplifier.

For both the X-1004 and the 1009, the gate-leakage currents given were measured with the actual circuit configurations described and are not intended to represent optimum values. Characteristic curves for the 1009 are shown in Fig. 8.

OTHER APPLICATIONS FOR MOS TRANSISTORS

The low value of gate-leakage current, small input capacity, and relatively high transconductance of these MOS units suggest their use in other applications such as mass spectrometers and high-vacuum photoelectric cells.

Their high-frequency characteristics also permit their use for pulse work down to a few nsec.

Preliminary tests indicate that this instrument is immune to interference from high-power rf sources.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Frank M. Wanlass of General Microelectronics, Inc., of Santa Clara, California, who is responsible for the research, design, and development of the X-1004 and 1009 MOS devices and who freely gave his time, knowledge, and devices in support of this work.

The author also wishes to thank H. Wade Patterson for supporting and facilitating this investigation.

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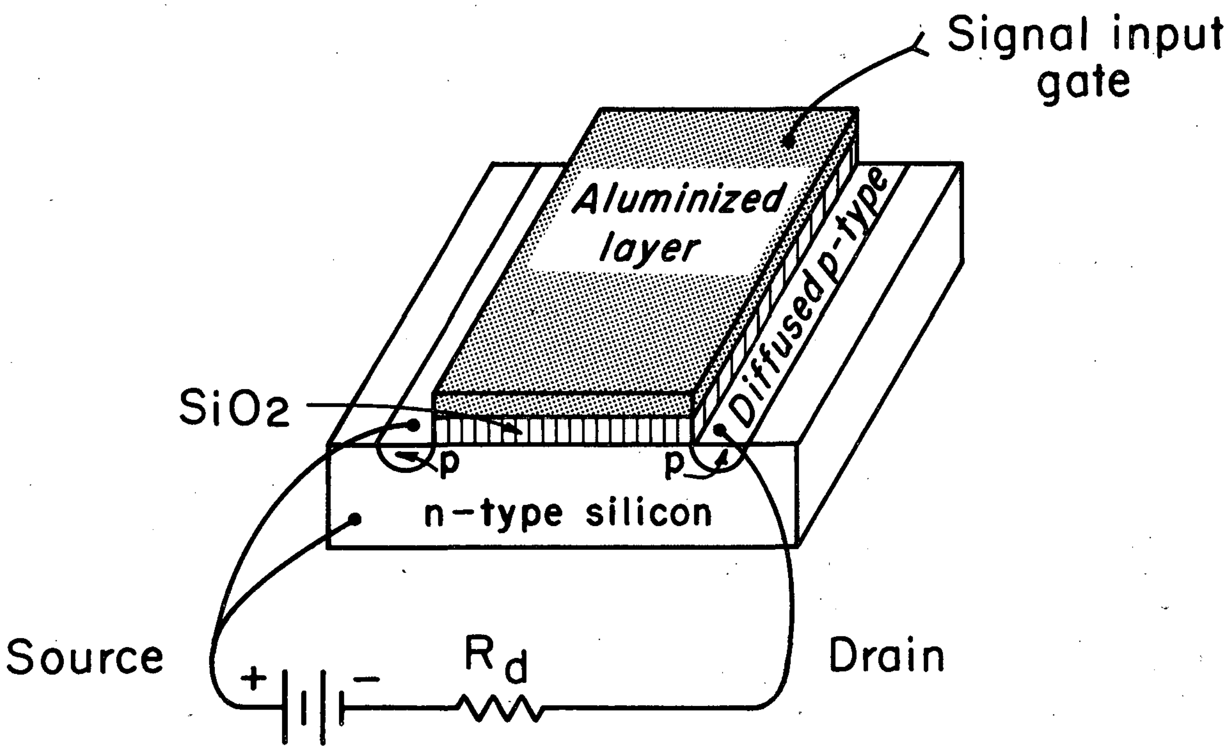

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Fig. 1. Planar diffused p-channel metal-oxide-semiconductor. $I_D \approx 10^{-9}$ A until $-V_{GS} \geqslant 4$ to 6 V. At this threshold voltage, a p-channel inversion layer is formed beneath the gate by the electrostatic repulsion of electron carriers from the region between source and drain, and attraction of holes into this region. The conductivity of this p-channel is then modulated by the gate potential. The layer of SiO_2 insulates the gate from the rest of the circuit and is responsible for the low value of leakage current.

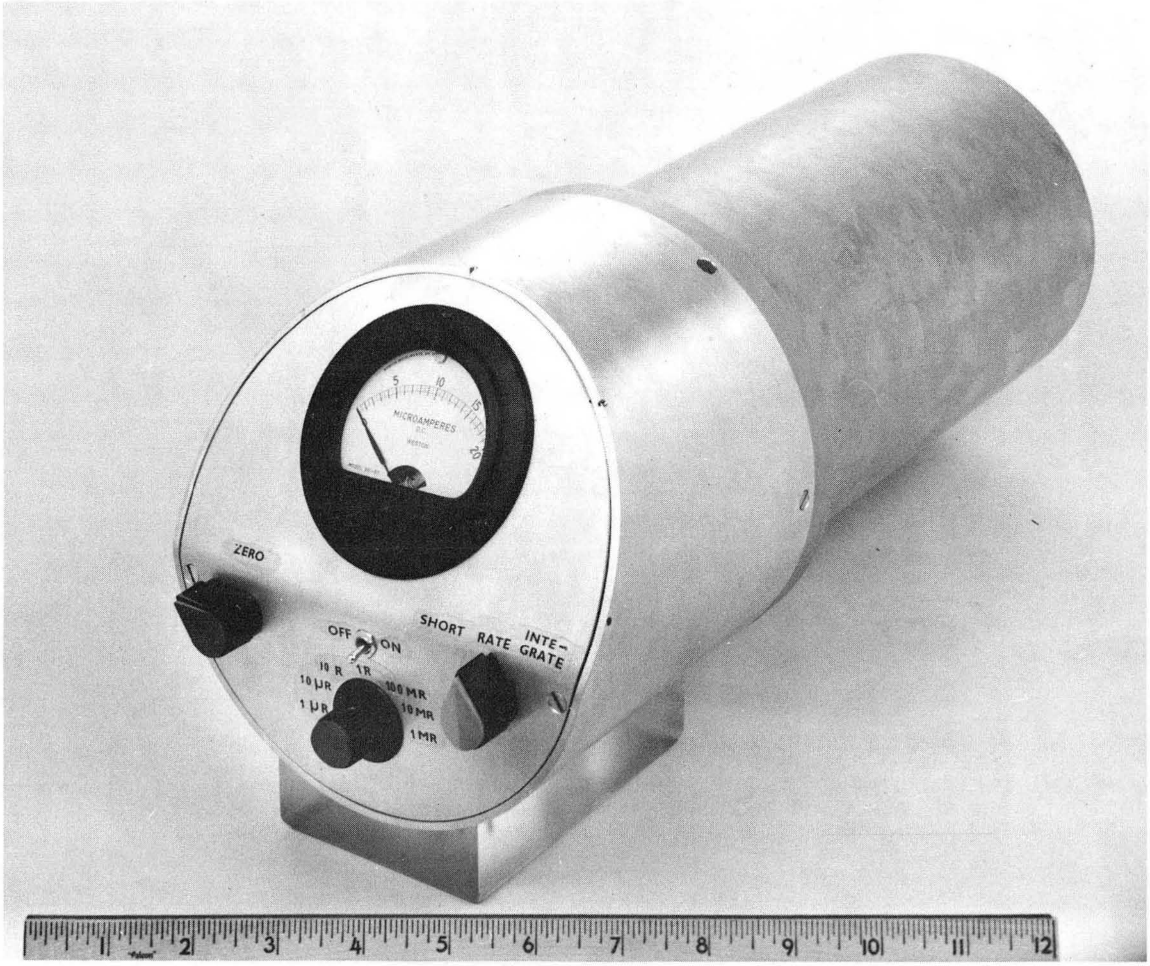

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Fig. 2. External view of complete instrument.

ZN-4296

Fig. 3. Internal view showing GM-e X-1004 supporting ionization-chamber anode wire.

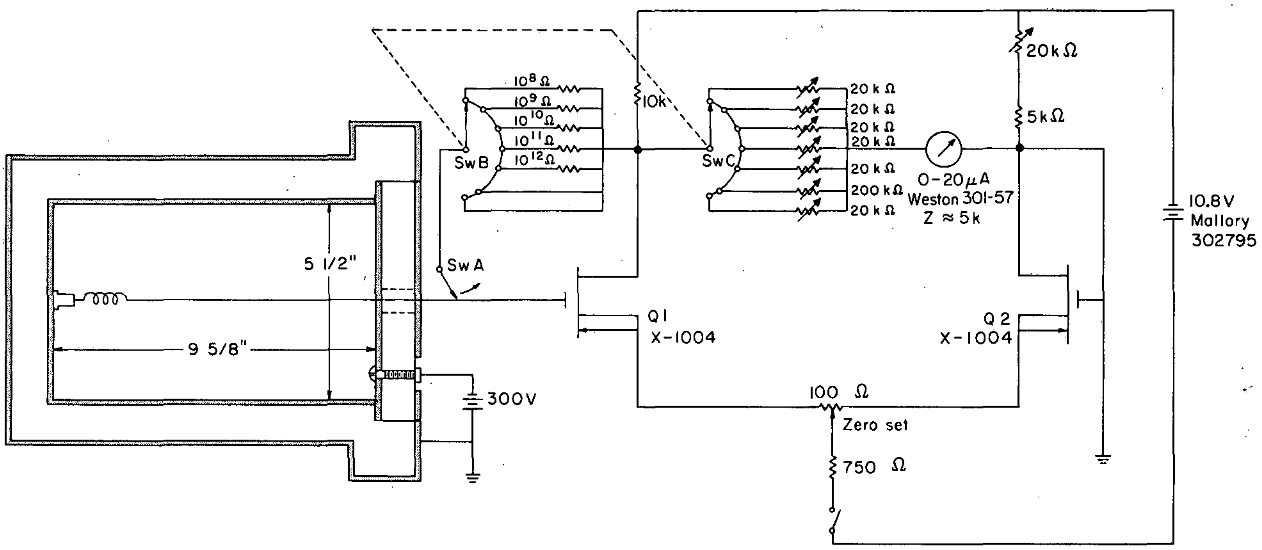

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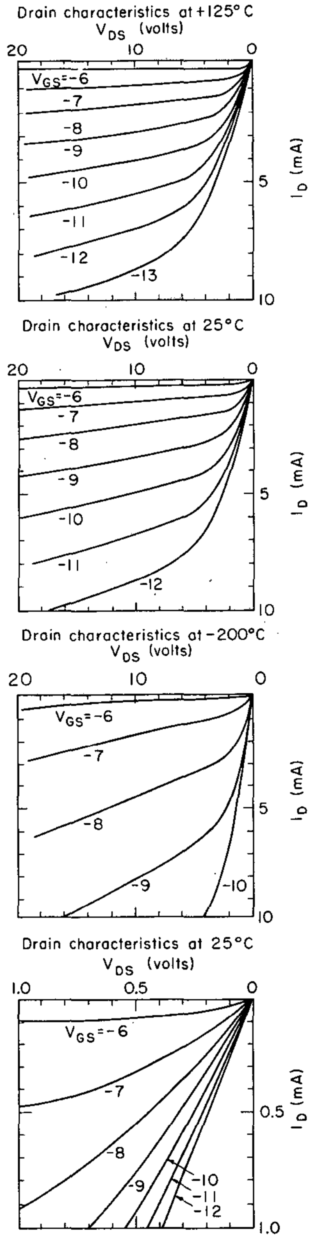
Fig. 4. Circuit schematic showing simplicity of design.

(a)



Drain characteristics at +125°C

Drain characteristics at 25°C

Drain characteristics at -200°C

Drain characteristics at 25°C

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Fig. 5 (a). Characteristic curves of MOS X-1004. Printed with permission of General Microelectronics, Inc., Santa Clara, Calif. V_{DS} versus I_D as a function of temperature.

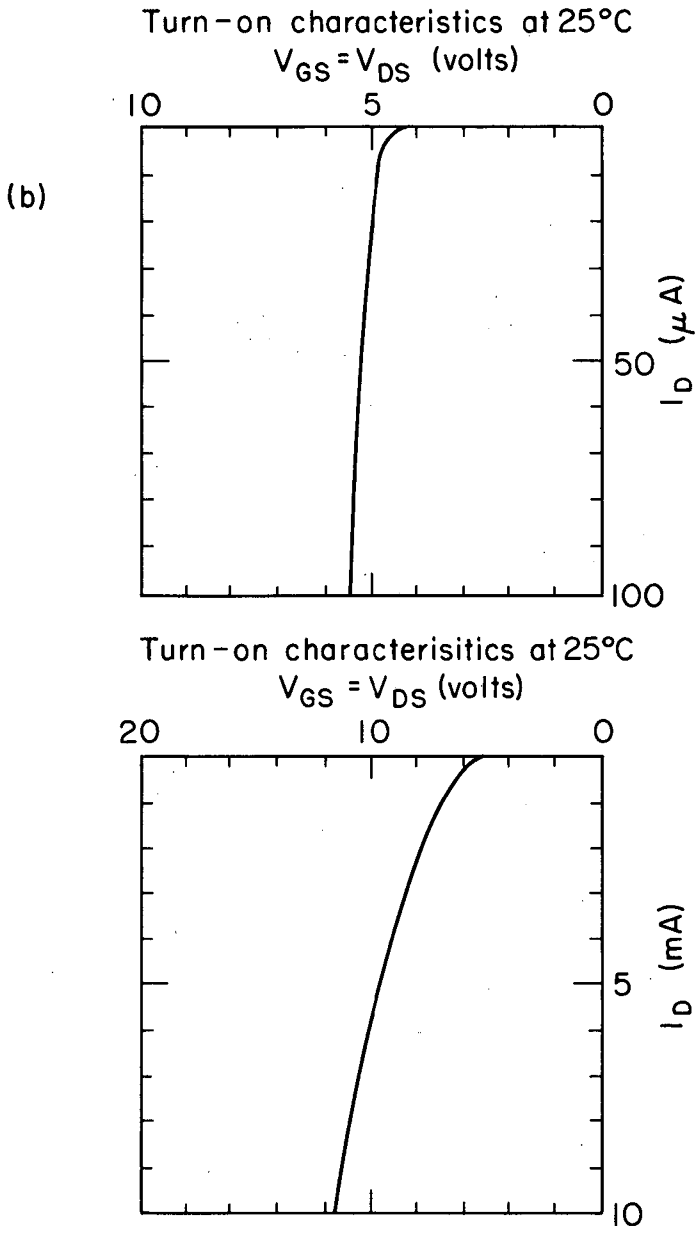

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Fig. 5 (b). $V_{GS} = V_{DS}$ versus I_D.

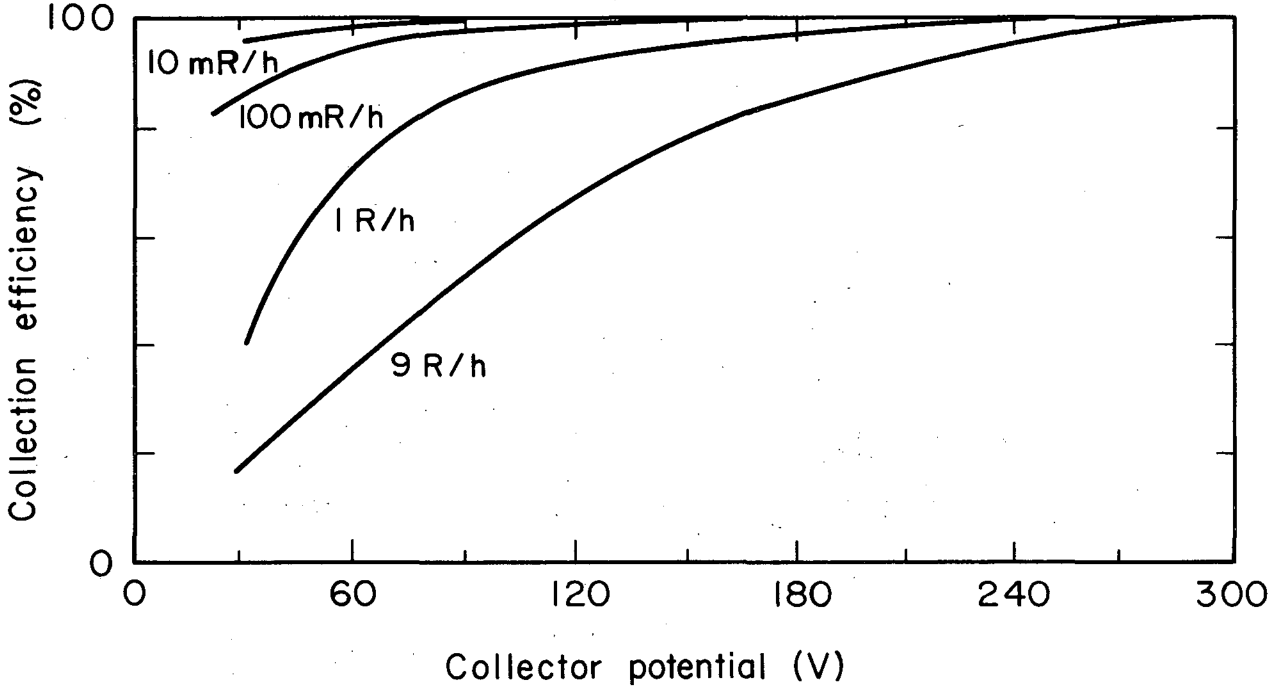

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Fig. 6. Collector potential (V) versus collection efficiency.

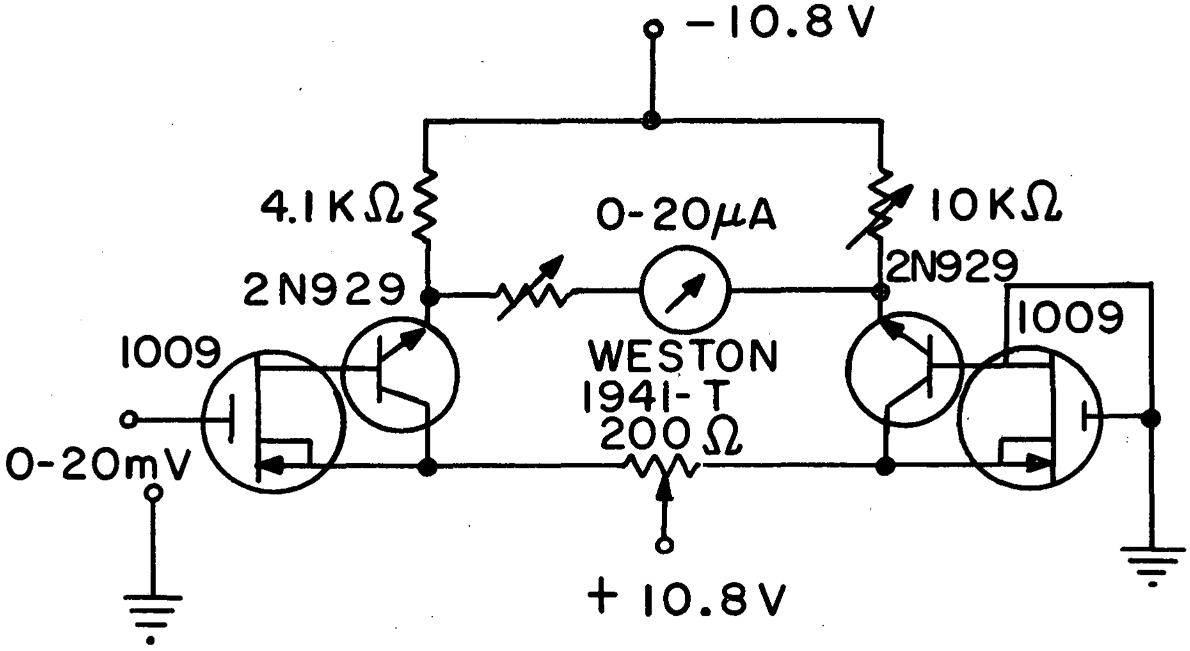

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Fig. 7. Current amplifier for 1009's. Full-scale sensitivity is 20 mV. For optimum performance, 2N 929's should be selected for high β and low I_{C0}.

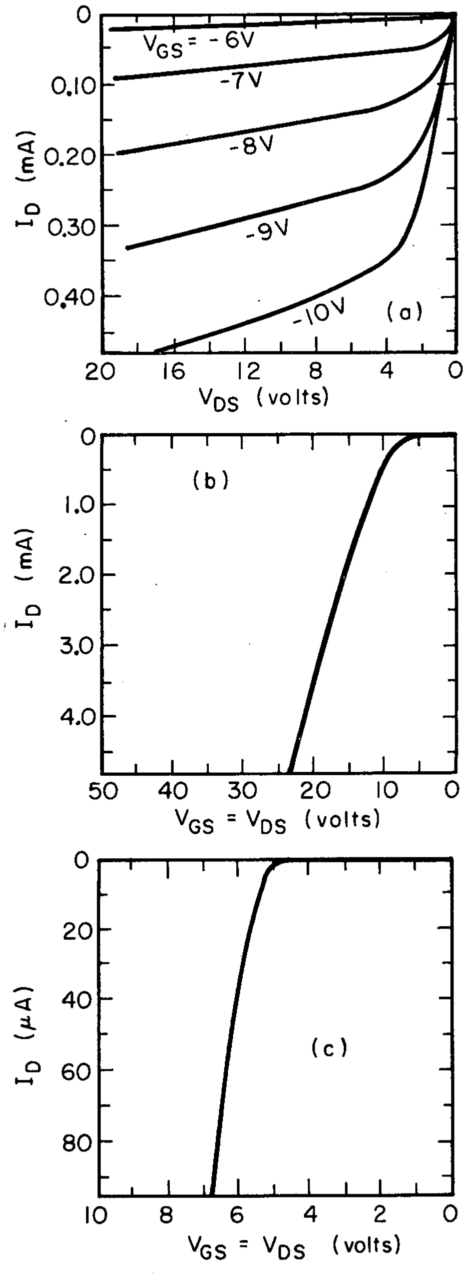

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Fig. 8. Characteristic curves at 25°C, MOS 1009. (a) Drain characteristics; (b) turn-on characteristics; (c) turn-on characteristics. Printed with permission of General Microelectronics, Inc., Santa Clara, Calif.