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ABSTRACT

This paper describes the effects of various ambients on the charge density and carrier mobility in a silicon — silicon dioxide interface. A method for measurement of these parameters is given. Results obtained with a number of devices prepared under various dry ambients are presented. From the results it is concluded that the freezing of the gaseous atoms into the lattice at the interface plays an important role in determining the electrical properties of the space-charge region.

1. INTRODUCTION

The possibility of stabilization of silicon surfaces by oxide passivation[1] has, during recent years, created considerable interest in the technology of planar devices. The present efforts directed toward development of a silicon insulated-gate field-effect transistor (FET) may be mentioned in particular in this context. A FET, being a majority-carrier device with high input impedance and with planar geometry, shows many attractive features in comparison with a conventional transistor.[2,3] All oxide-passivated planar devices encounter, in one way or another, the electrical effects of the space-charge region lying between the oxide and the semiconductor. Knowledge of these effects is therefore necessary to control and reproduce the device properties.

It is well known that a thermally grown oxide layer on silicon shows an interface characterized by a high concentration of donor states. Several authors[1,4,5] have measured the density of surface states produced under these circumstances and give a figure of the order of $5 \times 10^{12}/cm^2$. It is generally assumed that these donor states at the interface are a consequence of the thermal oxidation of the silicon surface, and the properties of the interface are therefore entirely determined by this process. The fact that different workers get the same result for the density of the surface states is a strong argument to substantiate this belief. However, as mentioned in reference 5, the surface-state density seems to be very much affected by the ambients (at high temperatures) under which the interface is treated. It was observed that the density of states is much less after treatment in a nonoxidizing environment than in an oxidizing environment.

This observation by Hansen and Goulding suggested the possibility of finding proper ambients under which the carrier mobility across the interface could be made very high. This might be important in the development of surface field-effect transistors. The frequency response of these devices depends directly upon the mobility of carriers in the $Si\text{-}SiO_2$ interface, and a high mobility would result in a high gain-bandwidth product. This paper describes a method for measuring the surface charge density and mobility and the conditions under which they can be favorably altered. Measurements are done in a typical field-effect arrangement; source and drain contacts are provided for a conducting channel whose conductivity is modulated by an applied dc field.

2. MEASUREMENTS OF CHARGE DENSITY AND MOBILITY

Consider a typical field-effect arrangement as shown in Fig. 1. The source and drain are separated by a conducting channel (n-on-p inversion layer in this case). We can do two types of measurements on this device,

(a) the impedance R of the inversion layer, and

(b) the negative voltage $-V_f$ on the field electrode that just inverts the layer.

With these measurements it is possible to find the charge density and the carrier mobility across the channel.

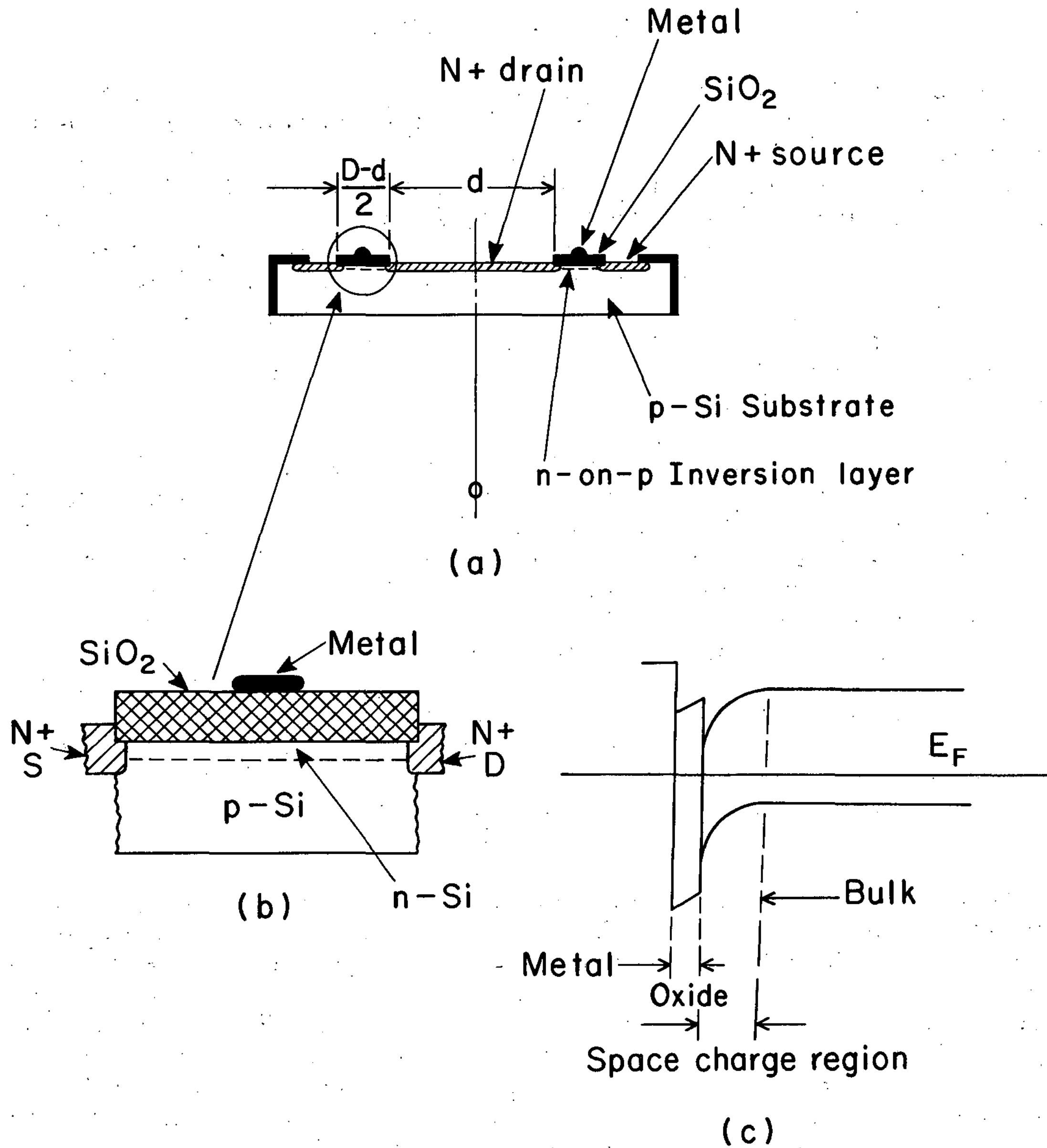


Fig. 1. (a) Typical surface field-effect device.
(b) Silicon — silicon dioxide interface (conducting channel) with source and drain contacts.
(c) Energy-band diagram of the donor surface states.

a. Impedance, R

The impedance dR of a small ring, of radius r and "length" dr, of the inversion layer is given by

$$dR = \frac{\rho}{W} \frac{dr}{2\pi r},$$

where ρ is the resistivity and W the depth of the layer. The total impedance is therefore

$$R = \frac{\rho_s \log_e D/d}{2\pi}, \tag{1}$$

where ρ_s is the sheet resistivity and D and d the outer and inner diameters of the layer. ρ_s is also given by

$$\rho_s = \frac{1}{N_e \mu_e q \cdot W} = \frac{1}{Q_s \cdot \mu_e}, \tag{2}$$

where μ_e is electronic mobility (effective value in surface layer),

and $N_e q$ is total charge per unit volume,
Q_s is charge per unit area in the inversion layer.

Combining (1) and (2), we get

$$Q_s \mu_e = \frac{\log_e D/d}{2\pi R}. \tag{3}$$

b. Pinch-off voltage, $-V_f$

For a quartz capacitor,

$$C = \frac{1.1\,\epsilon}{4\pi t}\ \text{pF/cm}^2,$$

where ϵ is the dielectric constant of quartz and t the oxide thickness. By measuring the voltage V_f on the gate electrode that just inverts the layer we can determine the charge density Q_s; V_f will just pinch off the channel current.

$$\therefore\ Q_s = \frac{1.1\,\epsilon}{4\pi t} \times 10^{-12}\, V_f \quad \text{coulombs/cm}^2. \tag{4}$$

From (3) and (4) the expression for carrier mobility is

$$\mu_e = \frac{1}{R\ V_f}\left(\frac{1.8\times 10^{12}\ t}{\epsilon}\ \log_e D/d\right). \tag{5}$$

In our setup we have

$$d = 10\ \text{mm}, \quad D = 14\ \text{mm}, \quad \epsilon = 4, \quad \text{and} \quad t = 7\times 10^{-5}\ \text{cm}.$$

The oxide thickness t is estimated from the data of Evitts et al.[6] We have, therefore, for the surface charge density and mobility, the expressions

$$Q_s = 5\times 10^{-9}\ V_f\ \text{C/cm}^2$$

and (6)

$$\mu_e = \frac{1.06\times 10^{7}}{R\ V_f}\ \text{cm}^2/\text{V-sec}.$$

3. PREPARATION OF DEVICES

Wafers, ≈ 30 mils thick, are cut from a high-resistivity (> 4000 ohm-cm) p-type silicon bar, along the ⟨111⟩ axis. They are then lapped, etched in 3:1 mixture of HNO_3:HF, washed in deionized water, dried, and loaded in a quartz rack for steam oxidation. Oxidation is carried out for 2 hours at 1000°C, in a furnace already filled with steam. This grows a 0.7-μ-thick layer of quartz[6] on the wafers. The wafers are then cooled in dry nitrogen to about 600°C and taken out of the furnace.

The parts of the quartz to be saved are then masked by painting the wafers with picein in trichloroethylene. These parts are the quartz ring (of i.d. 10 mm and o.d. 14 mm), the edge, and the back. The masking is done with a ruling pen, a brush, and a small motorized turntable. The quartz is dissolved away from the unprotected parts in a 1:1 NH_4F:HF mixture. The wafers are then washed in deionized water and etched in CP4 for 30 sec. They are then cleaned thoroughly in trichloroethylene, methyl alcohol, and deionized water and dried.

Wafers are now ready to be provided with the source and the drain contacts--at the parts from where the quartz was taken off--with the inversion layer under the oxide. A shallow diffusion of phosphorus into the oxide-free parts of the surface gives the necessary N^+ contacts. This is done in a diffusion furnace, at 900°C, by a 75-sec predeposit period in oxygen (1 liter/min) saturated with $POCl_3$, followed by a 30-min diffusion in selected ambients. In this work we have used three dry ambients,

(a) oxygen,
(b) nitrogen,
(c) nitrogen for 5 min, then nitrogen and 5% hydrogen.

Ambient (c) is carefully de-oxidized and dried, and during processess (b) and (c) precautions are taken to avoid possible streaming-in of oxygen into the furnace. The furnace is allowed to cool to about 600°C under the respective ambients before the wafers are taken out.

Quartz is removed from the back of the wafers by dissolving in HF. The wafers are finally given a 10-sec etch in dilute $NH_4F:HF$ (8:1) mixture, cleaned and dried. Then, with the device mounted on the turntable, a metal ring contact of soft solder is painted on the oxide ring.

4. TESTS AND RESULTS

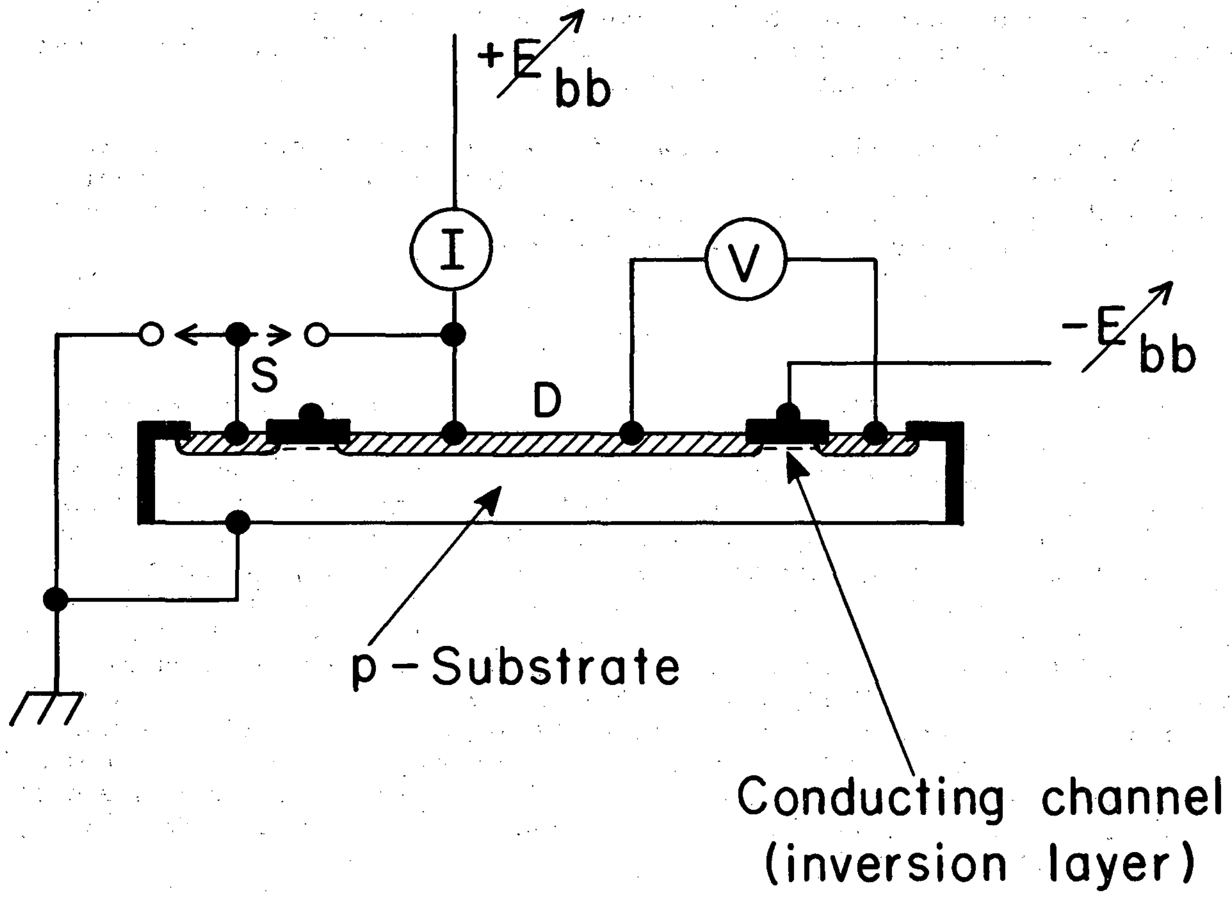
The channel impedance R and the pinch-off voltage V_f are measured by use of the circuit shown in Fig. 2. To avoid contact potentials, two spring contacts each are provided on the source and drain surfaces. During measurements the device is kept in vacuum. In this arrangement the source and the field electrode are first grounded and the drain is held at a positive potential. The total current I_t--the reverse current of the diode, I_d, plus the channel current I--and the voltage V across the channel are measured. A high-impedance voltmeter is used for measuring this voltage. The diode reverse current I_d is then measured by connecting the source to the same potential as the drain. This gives the channel current $I = I_t - I_d$. I is plotted as a function of V, and the constant ratio V/I at small values of V is taken as the channel impedance R. Typical plots are shown in Figs. 3(a) through 3(d) With a small value of V, the channel current is pinched off by applying a negative voltage to the gate electrode and V_f is measured. By use of Eqs. (6) Q_s and μ_e are calculated.

The experiments were performed with a number of devices prepared under different ambients; the results are given in Table I.

For devices in which the phosphorus diffusion was carried out in hydrogen and oxygen atmospheres we also measured the charge density and mobility at lower temperatures. The results are shown in Figs. 4, 5, and 6. The effective mobility at liquid nitrogen temperature for devices treated under hydrogen is approximately 2.5 times the room-temperature mobility. The charge density is about 70% of its room-temperature value. On the other hand, in devices treated under oxygen, the channel current gets pinched off at ≈ -75°C.

5. CONCLUSIONS

Whereas no attempt has been made to interpret these results in detail, they clearly indicate the important role played by the different ambients in determining the behavior of the semiconductor-oxide interface. It may be observed that it is the last high-temperature step that largely determines the properties of the interface. The gaseous atoms frozen into the lattice at the interface appear to govern the electrical properties of the inversion layer in a very decisive way.



MUB-3047

Fig. 2. Test circuit.

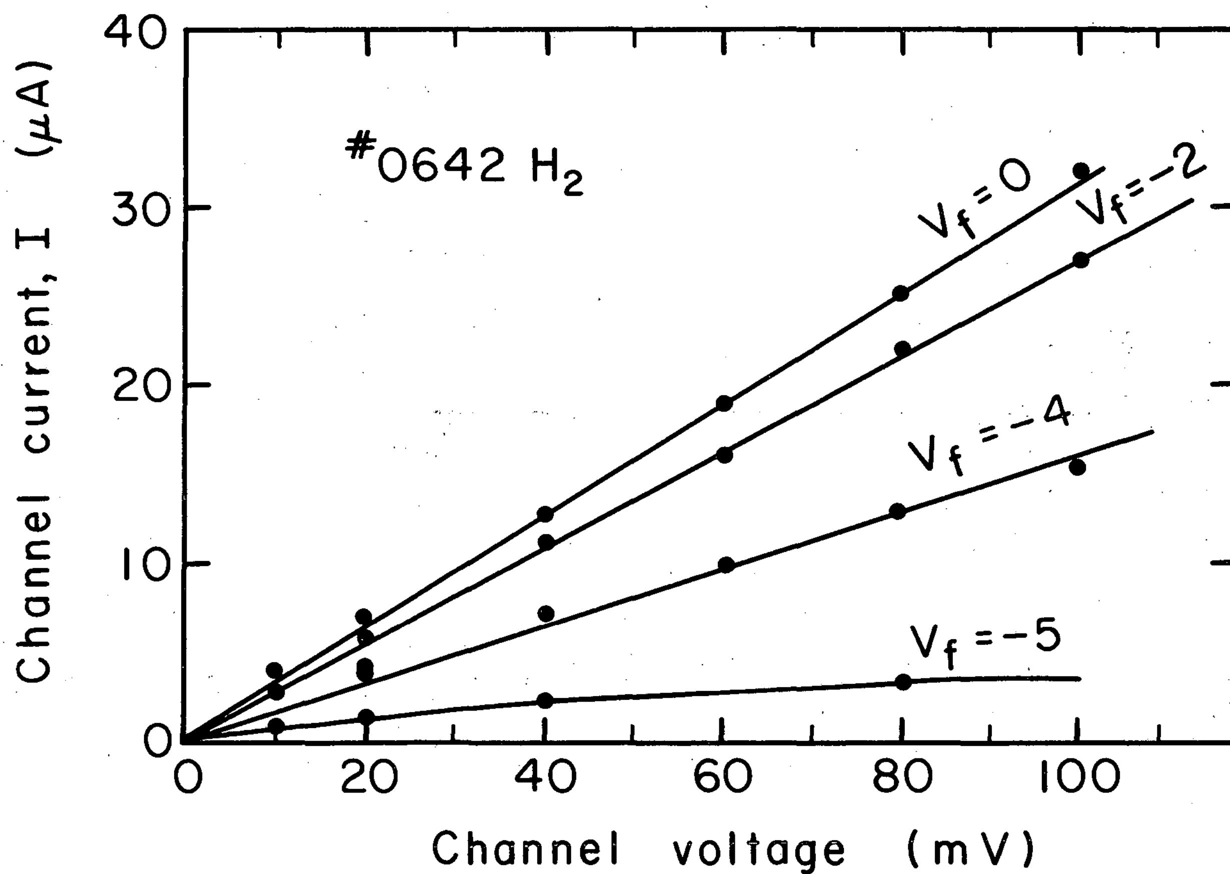


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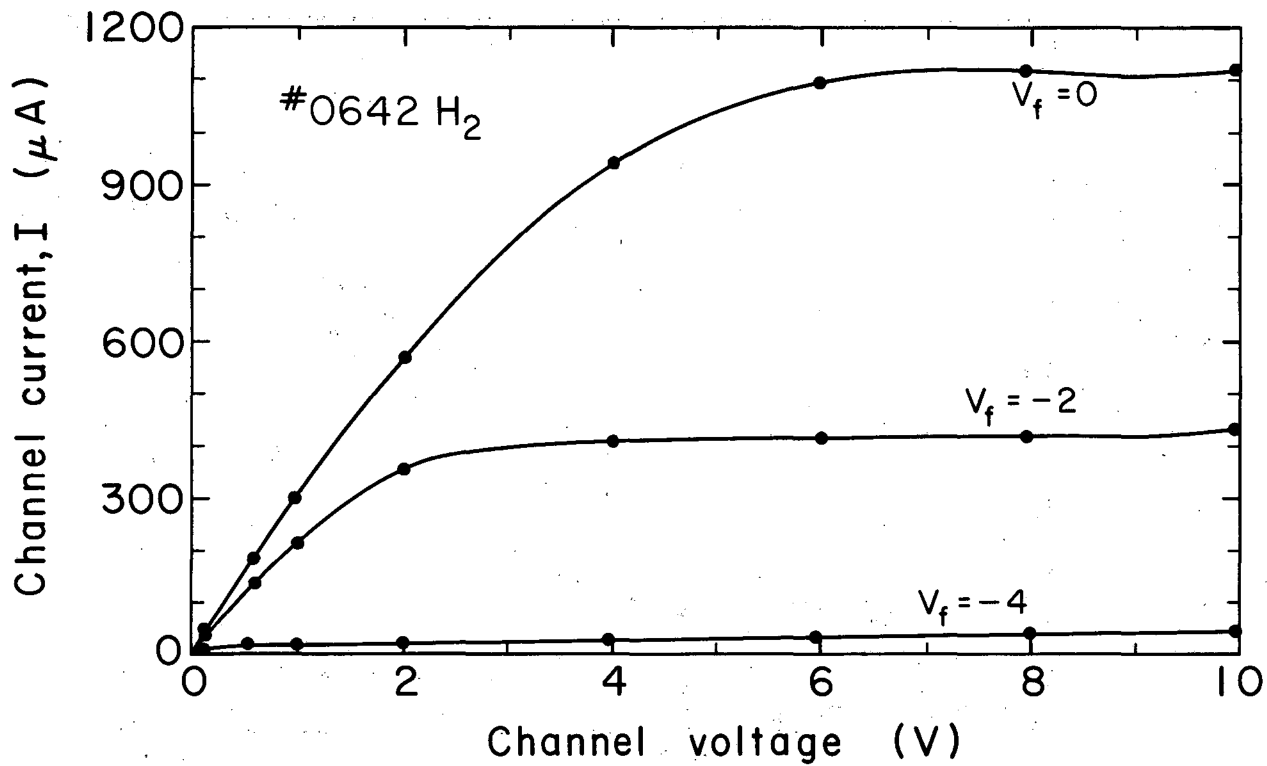
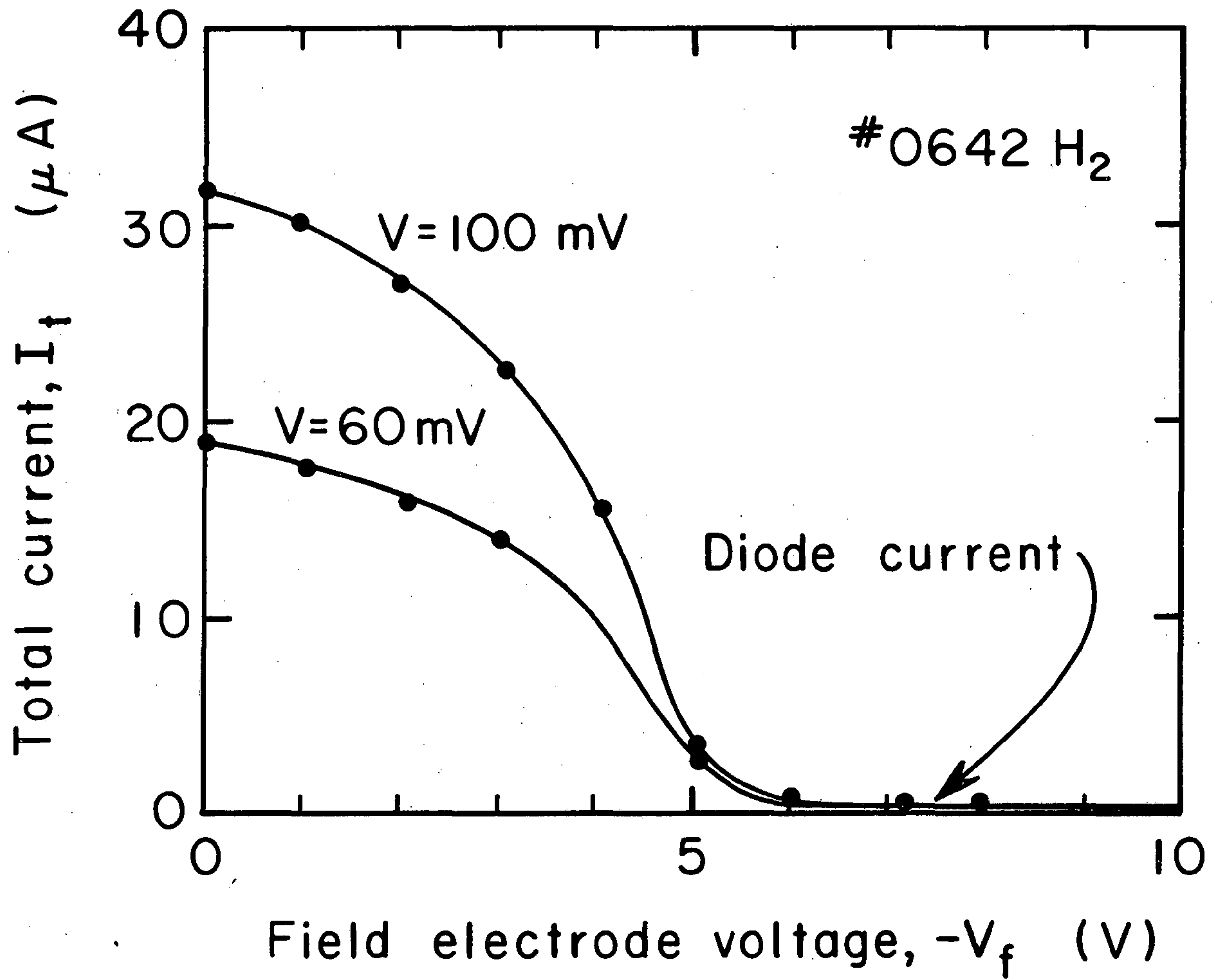
Fig. 3(a). Typical static characteristics of the device.



MUB-3049

Fig. 3(b). Typical static characteristics of the device.



MUB-3050

Fig. 3(c). Typical static characteristics of the device.

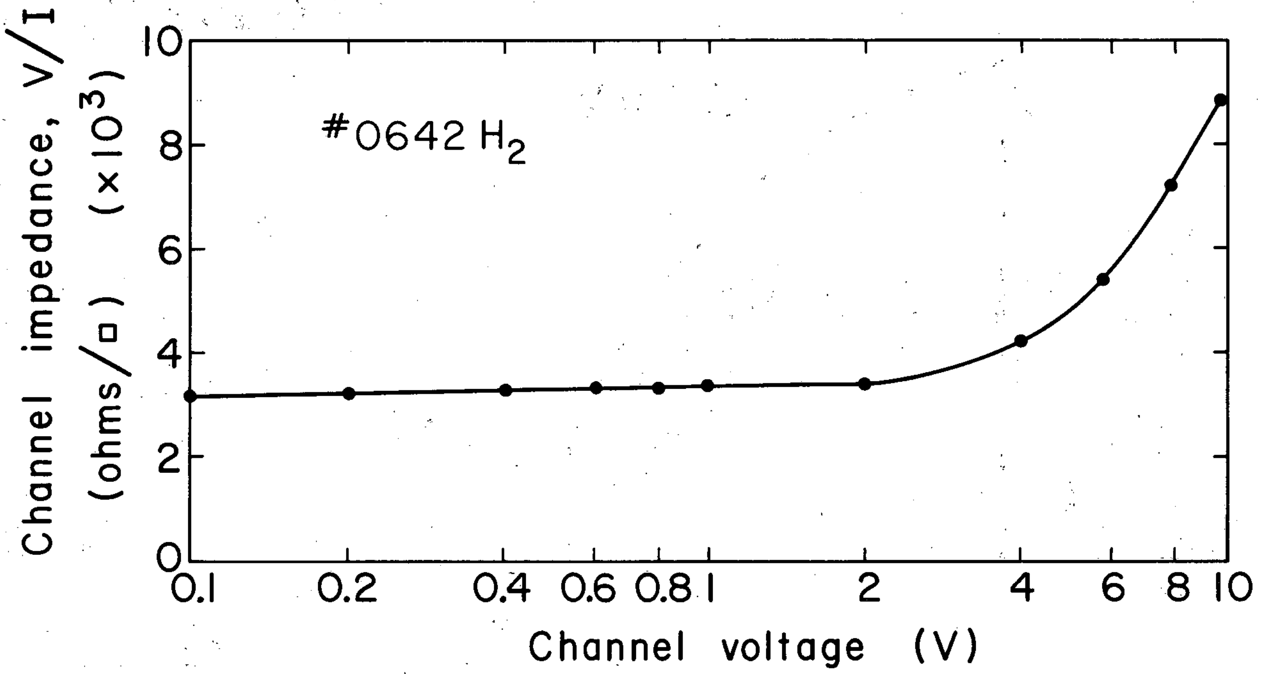


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Fig. 3(d). Typical static characteristics of the device.

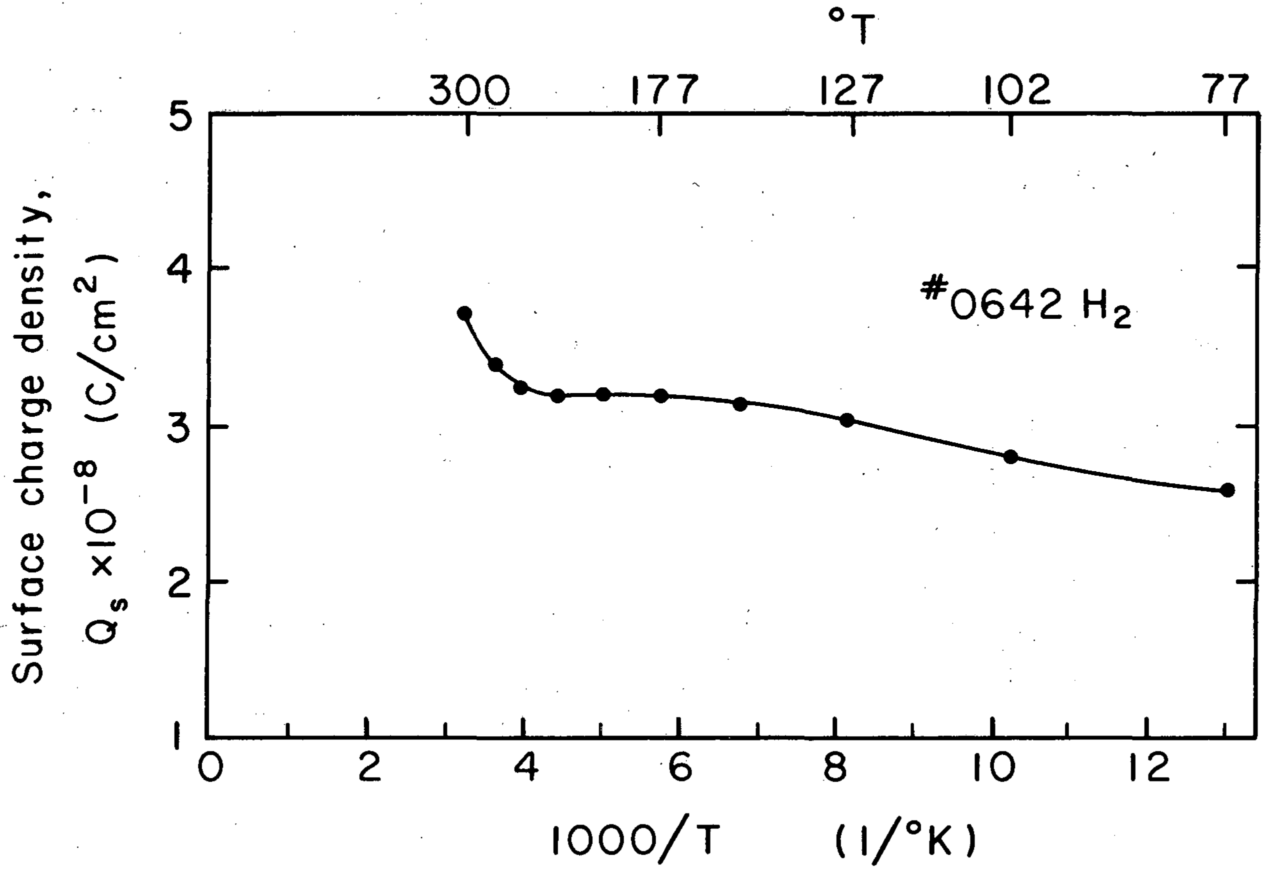

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Fig. 4. Surface charge density vs temperature for devices treated under hydrogen.

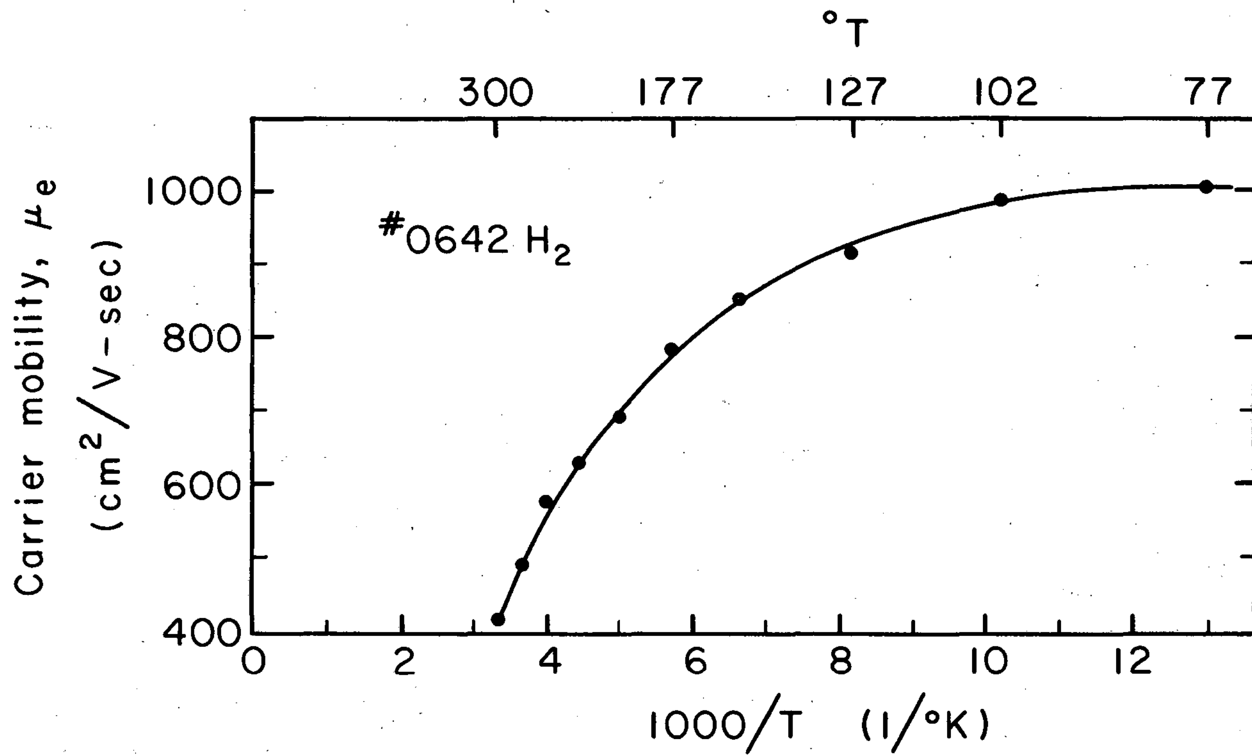

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Fig. 5. Surface carrier mobility vs temperature for devices treated under hydrogen.

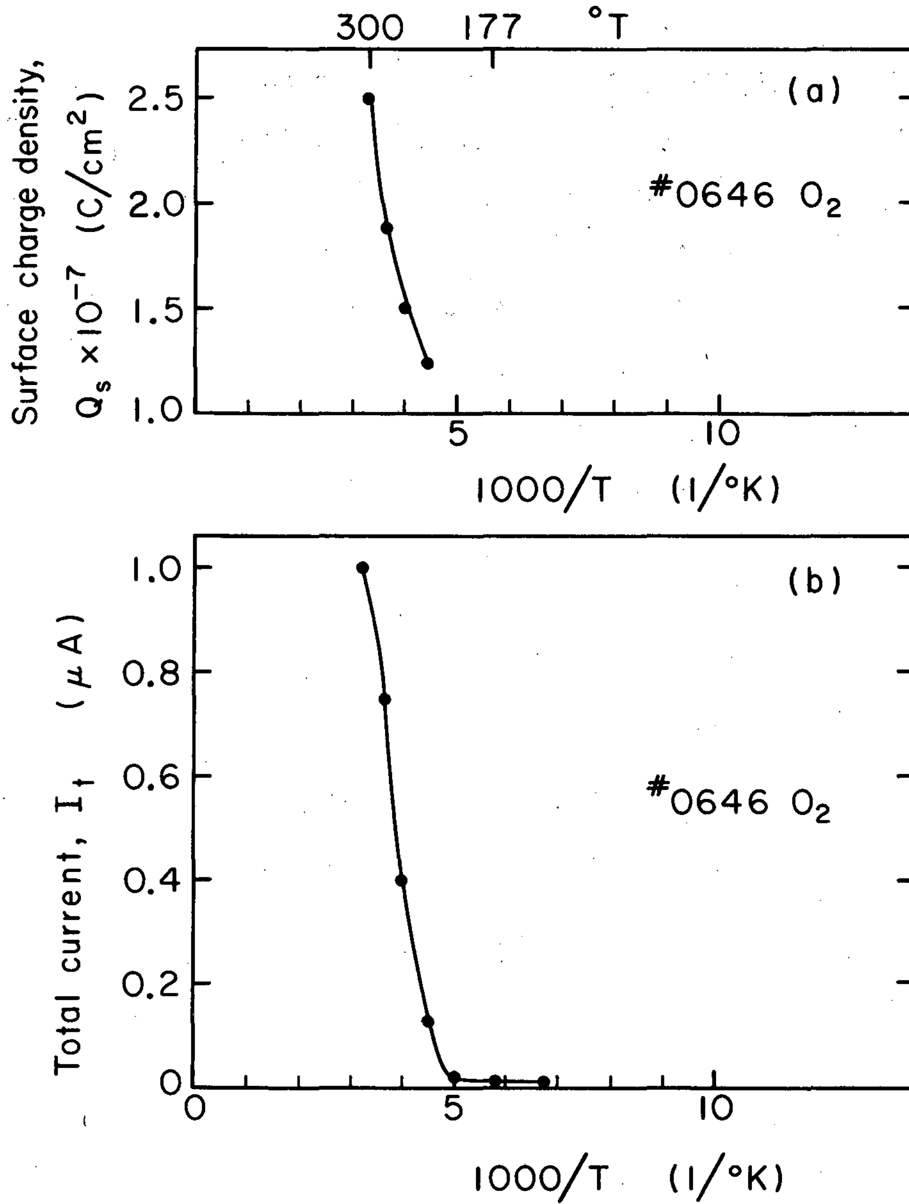

Fig. 6. Channel current and surface charge density vs temperature for devices treated under oxygen.

Table I. Effects of various ambients.

Device		R (ohm)	$-V_f$ (volts)	Q_s (C/cm^2)	μ_e (cm^2/V-sec)
1931	N_2	2.1×10^5	13.6	6.8×10^{-8}	3.7
2331		5.0	14.0	7.0	1.5
2332		10.0	14.0	7.0	0.75
2336		4.2	14.0	7.0	1.84
0643		9.0	15.2	7.6	0.77
0644		10.0	13.6	6.8	0.78
2532	O_2	2.8×10^4	45.0	2.3×10^{-7}	8.4
2534		3.1	47.0	2.4	7.3
0645		3.1	48.5	2.4	7.0
0646		3.8	50.0	2.5	5.6
3131	H_2	1.7×10^3	12.0	6.0×10^{-8}	505
3132		1.66	12.0	6.0	530
3133		2.5	6.8	3.4	620
3134		2.5	6.2	3.1	670
0641		3.0	6.4	3.2	550
0642		3.1	8.0	4.0	430
0646 (was given a final treatment in H_2.)	O_2	7×10^3	4.8	2.4×10^{-8}	315

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FOOTNOTE AND REFERENCES

* I. A. E. A. Fellow from Atomic Energy Establishment Trombay, Bombay, India.

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