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Measurements of Transfer Inefficiency of 250-Element Undercut-Isolated Charge Coupled Devices

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A 250-element charge coupled device is described in which the transfer electrodes are delineated and isolated using an undercut-etch technique. The device has metal electrodes on two thicknesses of oxide and is primarily intended to be operated in a two-phase manner. Measurements of transfer inefficiency as a function of frequency have been made on both n- and p-channel devices. Below 1 MHz, values of 4×10^{-4} per transfer independent of transfer frequency have been obtained. Above 1 MHz the transfer inefficiency progressively rises as the dynamics of charge motion limit the transfer of charge.

I. INTRODUCTION

A new method of fabricating charge coupled devices[1] (CCD) using the technique of undercut isolation has been reported recently.[2] A schematic cross section of a device made using this technique is shown in Fig. 1. The essential feature is a method of forming electrically isolated but self-aligned metal electrodes on two thicknesses of oxide. By connecting the electrodes in pairs, which may be done externally or using electrochemically plated regions on the device, as shown in Fig. 1, a two-level oxide structure[3,4] that may be operated in a two-

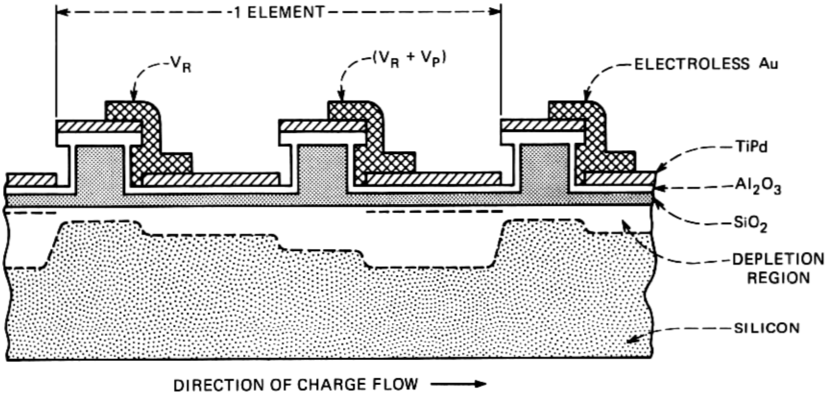


Fig. 1—Schematic longitudinal cross section of an undercut-isolated stepped-oxide CCD.

phase mode is obtained. This structure has several advantages over other structures. For example, compared to the three-phase structures, the geometrical constraints of having three phases, the requirement to fabricate 2- to 3-μm gaps, and the instabilities associated with the exposed oxide in these gaps are removed. Compared to other two-phase structures,[3–5] there is no need for a refractory metal technology or ion implantation, and the packing density of elements can be higher.

Test devices using undercut isolation and 250 elements long have been fabricated, and their transfer inefficiencies measured. The increase in number of elements from an earlier device[2] has allowed the small values of transfer inefficiency inherent in this structure to be measured accurately.

II. DEVICE FABRICATION

The 250-element CCD, which is the subject of this paper, was fabricated using the same photolithographic masks, except for two, as an earlier 500-element three-phase device[6] so that the undercut-isolated structure could be quickly evaluated. A photograph of one end of a finished device is shown in Fig. 2. The transfer region with the alternate thin and thick oxide levels is seen in the center of the photograph. The transfer electrodes are connected alternately on either side directly to two metal buses and via diffused cross-unders to two other buses. These cross-unders are not necessary for a two-phase CCD but were retained from the earlier three-phase device design to enable four-phase operation to be carried out for experimental purposes.

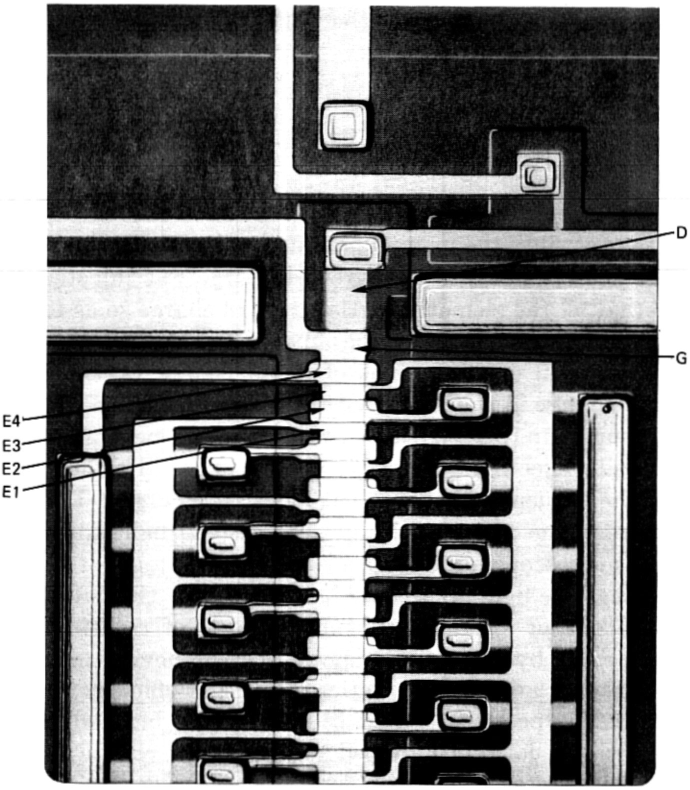


Fig. 2—View of the output section of a finished 250-element device, showing output diode D, output gate G, electrodes E1 and E3 over thick oxide, and electrodes E2 and E4 over thin oxide.

The transfer region is defined laterally by a "channel-stopping" diffusion that enhances the substrate doping. A device made exactly to the mask dimensions would have transfer electrodes that were 11 μm long over the thin oxide and 7 μm long over the thick oxide, with an 18-μm-wide channel. The devices were fabricated as described in an earlier paper[2] on both n- and p-type substrates.

III. MEASUREMENTS OF TRANSFER INEFFICIENCY

In order to measure the performance of the devices, voltages and pulses appropriate for either p- or n-channel devices, and two- or four-phase modes of operation were provided. Owing to circuit limitations, negative square pulses for driving p-channel devices up to frequencies of 10 MHz, and positive pulses up to 2 MHz, for testing n-channel devices were available. However, the n-channel devices could also be driven at up to 7 MHz using sinusoidal drive. As has already been mentioned, the device was made by modifying the design of an existing device, which had a very narrow transfer channel, so that the size of the output signal was not as large as is really desirable for easy and accurate measurements of transfer inefficiency. With a pulse voltage of 20 V, the maximum size of a charge packet was 0.5 pC. In all the measurements, a background charge was injected into the device so that all the elements carried a small charge so as to keep the interface states filled. Varying the amount of background charge in the range from 20 to 80 percent of a full charge packet caused no appreciable change in the measured transfer inefficiency.

At frequencies up to 2 MHz, the transfer inefficiency ϵ was measured by periodically injecting a single packet of charge into the device and observing the sequence of charge packets that emerged. The injection of charge was done either optically with a small light spot projected through a microscope or electrically. An advantage of the optical method is that the light spot could be moved near the output and the form of the output signal for a small number of transfers could be established. Also, by moving the spot along the device and observing the output signal, any discontinuities in transfer efficiency at a region of poor transfer, possibly caused by a partially blocked channel or an open electrode, could be detected and the device rejected. Obtaining a numerical value for ϵ from the observed sequence of output charge packets is based on comparison with the expected sequences[7,8] for different values of transfer inefficiency product $n\epsilon$, where n is the number of transfers.

Particularly for measuring values of $n\epsilon > 1$, it is more accurate to use another technique in which a sinusoidal input at different frequencies is fed to the device and the amplitude of the output measured. The frequency response of the device corrected for the response of the output amplifier is then plotted. Comparison with the theoretical response curves[7] enables values of $n\epsilon$ to be obtained. The advantage of this method is that values of transfer inefficiency for high values of drive frequency f_o could be obtained using input signals and amplifiers with bandwidths much lower than the drive frequency f_o.

IV. MEASURED VALUES OF TRANSFER INEFFICIENCY

A plot of transfer inefficiency versus frequency for both n- and p-channel devices operated in the two-phase mode is presented in

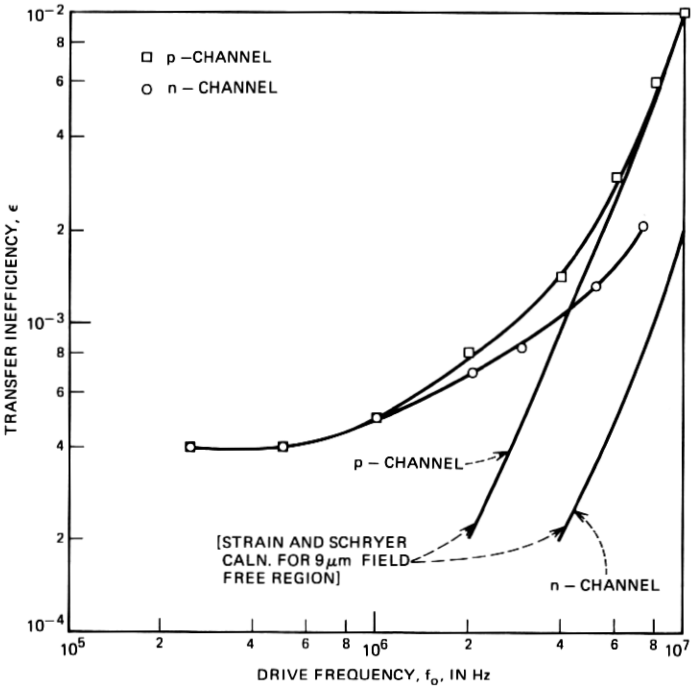
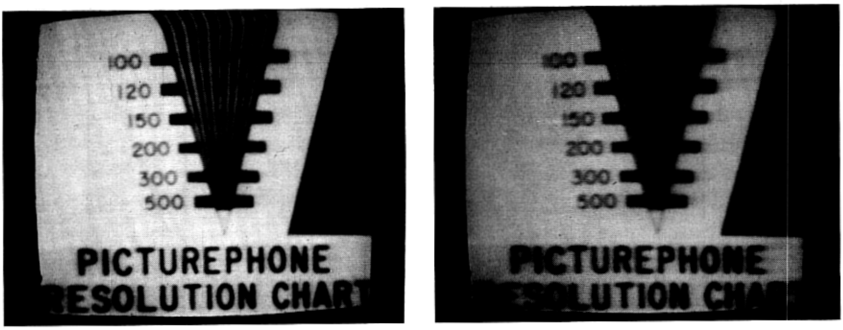


Fig. 3—Measurements of transfer inefficiency (per transfer) for both n- and p-channel undercut-isolated CCDs. The theoretical values for p- and n-channel devices assuming a 9-μm field free region under the transfer electrodes on the thin oxide have also been plotted.

Fig. 3. The transfer inefficiencies for both the p- and the n-channel devices, as predicted by calculations of charge motion[9] for devices with mobilities of 200 and 400 $\text{cm}^2\ \text{V}^{-1}\text{s}^{-1}$ respectively, are also shown on the figure. A 9-μm-long field free region is assumed under each electrode on the thin oxide, since the electric fields from the neighboring electrodes will penetrate at each end of the electrode.

Referring to Fig. 3, the transfer inefficiency of the devices appears to be flat below 0.5 MHz, perhaps due to limitations caused by interface states.[10] Above 0.5 MHz, the transfer inefficiency progressively degrades until, for the p-channel device, it rises exponentially following the theoretical curve. The rounding of the experimental curve is due to the joint contributions of the interface states and the dynamics of charge transfer. The greater carrier mobility in the n-channel devices is reflected in the lower transfer inefficiencies of these devices at frequencies in excess of 1 MHz.



DIRECT DELAYED

Fig. 4—Showing the use of a 250-element n-channel undercut-isolated CCD to delay a *Picturephone*® video signal by 121 μs. The direct (undelayed) display is seen on the left and the delayed display on the right.

The transfer inefficiency per transfer obtained on the p-channel device operated in the four-phase mode at 1 MHz was 5×10^{-4}, which is about the same as that obtained in two-phase mode. However, in the two-phase mode, only half the number of transfers are required for a CCD with the same number of elements so that a device operated in this way has half the transfer inefficiency product $n\epsilon$ of one operated in four-phase mode. This is an important observation, not only because of the improved performance, but because of the additional advantage that two-phase interconnection gives to the design of functional devices.

The p-channel device was used, as described in more detail elsewhere,[11] to delay a *Picturephone*® video signal by 121 μs with barely noticeable degradation in the display as shown in Fig. 4.

V. CONCLUSIONS

The structure described has given transfer inefficiencies which are more than adequate to permit the design of devices for many applications. The two-level oxide structure with electroplated interconnections leads to some relatively simple designs of devices for various applications. The active region of the device is fully protected with a double-layer oxide and there are no exposed regions of oxide which can charge up and degrade the performance of the devices. There is no need for refractory metal electrodes and high-temperature processing to obtain a good second-level dielectric layer for insulation, or for fine features to be etched in the metallization as required in other structures. In addition, there is no critical reregistration required in the cell, so that compared to other structures, a smaller cell may be fabricated given the same fabrication tolerances. This would lead to higher packing densities and a capability of operating at higher frequencies. An encapsulant may be required to protect the undercut regions from dirt, damage, and electrical breakdown.

VI. ACKNOWLEDGMENTS

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