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pChannel ChargeCoupled Devices with Resistive Gate Structure

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films of In, Sn, and Bi, which, because of their thermodynamic properties, can be made to exhibit prominent liquidlike nucleation and coalescence characteristics,[8] which is a central feature of the charge-force concept[1] and of the explanations of observed electric field effects.[2,7]

Figure 2 illustrates typically the absence of electric field effects in the thin films studied in this investigation. Figure 3 shows for comparison with Fig. 2 the prominent effects substrate temperature causes in the nucleation and growth processes, and illustrates the unambiguous liquidlike characteristics of films grown on substrates where $T\approx 0.8\,T_m$ (T_m = melting temperature[8]).

Finally, it is worth noting that, aside from the well-established effects of temperature, pressure, and evaporation rate on the nucleation and growth characteristics of vapor-deposited thin metal films[9–11] variations in the substrate morphology can promote growth variations having a full range of structural characteristics.[12,13] An example of this phenomenon is shown in Fig. 4.

In summary, it has been shown in the present work that no unambiguous changes in vapor-deposited growth are induced by the application of an electric field $E \leq 10^3$ V/cm in the plane of the substrate. Electric fields are therefore insignificant in the systematic promotion of film growth and properties, particularly when compared with other parametric variations, e.g., temperature, pressure, evaporation rate, and mean film thickness. Certainly this does not preclude effects of entrapped charges in the vapor stream, ionization effects,[14–16] and direct electron-charge effects which arise for films grown inside the electron microscope.

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p-Channel Charge-Coupled Devices with Resistive Gate Structure

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Charge-coupled devices with resistive material covering the oxide between adjacent gate electrodes are described. These devices were fabricated incorporating a continuous strip of deposited silicon with doped and undoped regions. Since the surface potential under the gap can be controlled using this structure, reliable *p*-channel devices with nonoverlapping gate electrodes can be made which have all the advantages of *p*-channel silicon gate technology. Transfer efficiencies greater than 99.3% per transfer have been obtained at up to 1-MHz bit rates for three-phase experimental devices.

For efficient transfer of carriers in charge-coupled devices,[1,2] it is necessary that the silicon—silicon-dioxide interface is depleted in the regions between adjacent gates. One way of achieving this condition, regardless of the type of the substrate doping, is to use overlapping gate structures with two layers of conductive materials.[3,4]

For a nonoverlapping gate structure,[2,5] however, the surface potential under the bare oxide between adjacent gate electrodes is extremely hard to control externally. Conceptually, we can reduce the gap length to be comparable to the oxide thickness and utilize the fringing field in a lowly doped substrate. In practice, however, gap lengths less than 2 μ give a serious yield problem with present day photomasking technology while the oxide thickness is usually only about 0.1 μ. As a result, gap lengths are typically 2.5 μ or more, and the surface potential under the gap depends primarily on Q_{ss} at the interface and on the charge condition of the bare oxide surface, both of which are not controllable externally. Since Q_{ss} is positive, it tends to accumulate electrons at the interface for *p*-channel devices. (Because Q_{ss} tends to deplete the surface of a *p*-type substrate, a resistive gate structure may not be an absolute necessity for *n*-channel devices.[6] Reliability of the device, however, will increase with a resistive gate structure for both *n*- and *p*-channel devices.) Therefore, successful operation of *p*-channel charge-coupled devices with a nonoverlapping gate structure depends critically on the condition of the bare oxide, which is almost unpredictable. Although the surface leakage of the oxide layer will improve the situation by allowing the oxide surface to charge negatively, this depends critically on humidity, temperature, and device history, and reliable operation of a sealed device is still a problem. The problem can

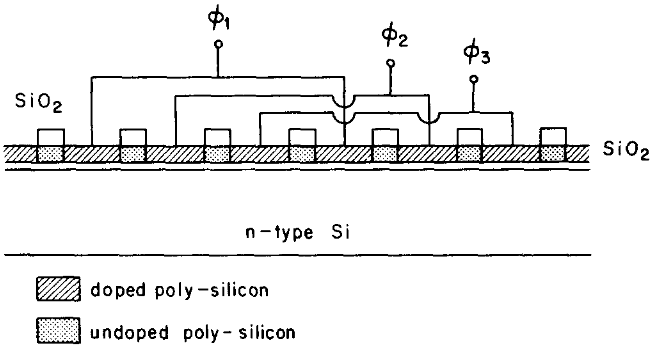

FIG. 1. Cross section of p-channel silicon gate charge-coupled device using doped and undoped poly-silicon.

be solved by depositing a resistive material between the gate electrodes, thereby controlling the potential of the oxide surface. The device described here utilizes undoped poly-silicon as the resistive material[7,8] and doped poly-silicon as the gate electrodes.

Figure 1 shows the cross section of a three-phase structure using doped and undoped poly-silicon. Undoped poly-silicon is deposited at 850 °C over thin oxide of about 0.1-μ thickness. An oxide layer is then grown over the poly-silicon and etched to define the gate areas. The exposed poly-silicon is doped with boron in a predeposition furnace to form the highly conductive gate electrodes. The predeposition process is done as the last high-temperature process in fabricating the device to prevent shorts between the gates due to lateral diffusion. The resistivity of undoped poly-silicon is about 10^5 Ωcm.[7] For 0.5-μ-thick poly-silicon, this gives 2×10^9 Ω/sq sheet resistivity. Because of the high sheet resistivity, the driving power requirement will be extremely low. As an example, if the gate electrodes are 50 μ wide and separated by 5 μ, the power dissipation in the undoped poly-silicon will be less than 0.5 μW/gap for 10-V clock pulses. The time constant for charging this resistive region will be about 20 μsec, and hence the potential gradient will not be linear for operating frequencies above about 100 kHz. Nonetheless, the potential will be *controlled* at some average of the clock voltages and will not be allowed to assume an arbitrary value.

Eight-bit three-phase charge-coupled shift registers similar to those reported by Tompsett *et al.*[5] have been fabricated on n-type substrates with undoped poly-silicon between the gate electrodes. The center-to-center spacing of the gate electrodes is 25 μ, and the oxide thickness is 0.1 μ. The substrate doping level is either 2×10^{14} or 10^{15} cm^{-3}, and the gap length is 5 or 10 μ. All these devices have been operated successfully and dependably, using three overlapping clock pulses. To ensure depletion at the interface, the clock pulses have dc offset voltage which is a little above the threshold voltage of the MOS gate structure. Figure 2 shows typical input and output waveforms of a device operating at 500 kHz. The driving clock pulses have 10-V amplitude with 0.1-μsec rise time and 0.6-μsec fall time. The input signal, shown as the upper trace, is an eight-bit word which consists of ONE's and ZERO's. A ONE is represented by a negative pulse, and a ZERO is represented by the absence of the pulse. The lower trace is the current at the output diode. Transfer efficiencies have been measured by applying an eight-bit word consisting of a single ONE and seven ZERO's and by integrating the currents at the input and output diodes corresponding to the main signal. The trailing signals appearing at the output diode due to transfer inefficiency are excluded in the above integration. With 10-V clock pulses, over-all efficiency greater than 85% has been obtained routinely for up to 1-MHz bit rates. This corresponds to 99.3% per transfer. The dependencies of the transfer efficiency on the gap length and the substrate doping level were too small to be found within the experimental accuracy. The yield for these devices was larger than 50%. On the other hand, for similar devices with bare oxide, only a few working devices were found.

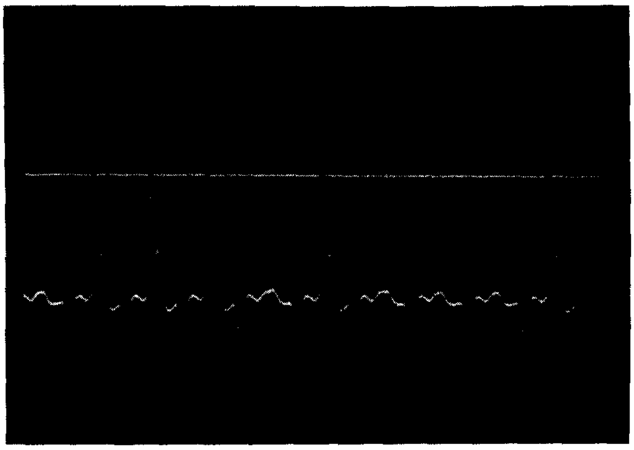

FIG. 2. Typical input and output wave forms. Horizontal scale: 2 μsec/div. Vertical scale: 5 V/div, upper trace; 10 μA/div, lower trace.

In conclusion, using undoped poly-silicon between the gate electrodes, it is possible to make a dependable p-channel charge-coupled device with nonoverlapping gate electrodes over a wide range of gap lengths and substrate doping levels. These devices can be fabricated with all the advantages of standard p-channel silicon gate technology, including the availability of a second conductor layer for interconnections. Since the gap length and substrate doping level are no longer critical device parameters, the yield problem with small gap length is removed and substrate doping can be chosen to suit other requirements.

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Interference Effects in Laser-Modulated Electron Beams*

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A new class of electron interferometers is proposed that make use of a laser-modulated electron beam. The observable interference arises in second-order processes, since the first-order interference oscillates rapidly and averages to zero. It is shown that the detected signal varies sinusoidally with the separation of two sequential modulators, thus generating a fringe pattern with peak-to-peak spacing that may be smaller or larger than the laser wavelength. It is suggested that such devices could be used to detect and study the modulation process and, because they operate with massive charged particles, to perform a wide variety of new experiments and high-precision measurements.

Considerable interest and controversy has arisen from a recent experiment[1] which seems to indicate that an electron beam can be appreciably modulated by a laser beam using a solid material as a coupler. In that experiment, the electrons passed through a thin crystalline film irradiated on its edge with a focused laser beam, and then impinged on a nonfluorescent screen. Light of the same color as the laser was reportedly emitted from the regions on the screen where the electrons impinged, and this was taken as evidence of electron modulation. The controversy has developed from the lack of a suitable model to account for the emitted intensity, and the failure of others[2] to reproduce the experiment may indicate that the original observations are not easily explained. Nevertheless, there appear to be reasonable models for modulation processes, and recent calculations indicate that a modulation of several percent can be achieved with present techniques.

Quantum-mechanical calculations of the modulation process are straightforward.[3] The incident electron wave is scattered into a coherent superposition of spherical waves of various frequencies; interference between these waves and the incident waves produces modifications of electron density, current, etc., that vary in space and time. The detection of such modifications (hence, the modulation) presents a formidable experimental problem, however. The electrons may be pictured as oscillating rapidly among the various energy eigenstates, and linear detectors which cannot follow these oscillations must take some sort of average over many cycles. Hence, all the first-order interference effects will average to zero, making the modulation unobservable. Recently, Favro and co-workers[4] have shown that, if electrons in a coherent superposition state strike an appropriately resonant target, the excitation cross section will be larger than the incoherent value, and this could provide a means of detecting and studying the modulation process. However, such mechanisms are cooperative electron effects and depend upon the square of the beam current.

We wish to point out that, if the electron beam is modulated twice, either by passing through two crystals or by using two laser frequencies, new interference effects occur which could be observable. In these processes, the second modulation acts like a coherent detector or demodulator for the beam from the first modulator. Such a device would make possible observation and study of the quantum-mechanical modulation processes and new high-precision measurements and experiments.

Consider the experimental arrangement diagramed in Fig. 1, in which an electron beam passes through two thin solid films a and b illuminated by laser light of various frequencies and is detected at some distant point r. We assume the individual electrons can be described by a wave function $\psi(\mathbf{r}, t)$, which evolves in time according to the Hamiltonian $H_0(\mathbf{r}) + V(\mathbf{r}, t)$, where $H_0(\mathbf{r})$ represents the free-particle Hamiltonian. The electon+

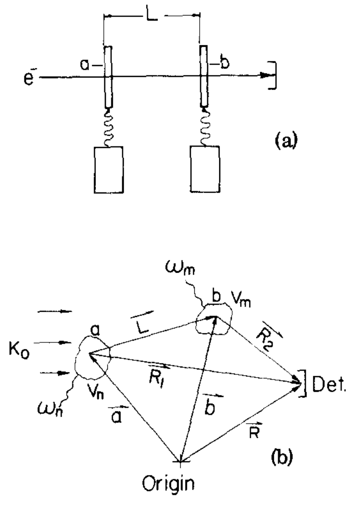

FIG. 1. Schematic of proposed laser-modulated electron interferometer. (a) Diagram of a two-crystal transmission interferometer using two lasers. (b) Structural diagram indicating the vectors referred to in the text.