Charge-Packet-Initiated Switching of Metal–Tunnel-Oxide–Silicon (MTOS) Junctions

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Abstract—**We report the switching of a bistable metal–tunnel-oxide–silicon (MTOS) junction from a low-current state to a high-current state by the insertion of a charge packet of minority carriers from a charge-coupled device input structure. For the 33-Å tunnel oxide reported in this letter, a switching threshold of 630 pC for a 40 mils^2 device area was observed. The transient switching time is approximately *10–100 ms*, depending upon the size of the injected charge packet.**

I. INTRODUCTION

THE metal-tunnel-oxide-silicon (MTOS) device structure has been shown to exhibit bistable behavior in its reverse-bias current-voltage characteristic for devices on n-type substrates with oxide thicknesses in the 30–45-Å range [1]-[5]. In the low-current state, the semiconductor is deeply depleted and only a small voltage drop across the oxide is present. In this state, the thermal generation of holes in the deep depletion region and nearby bulk is balanced by hole transport through the oxide barrier. In the high-current state (for applied voltages exceeding approximately −3.0 V), most of the voltage drops across the oxide, and the device exists in a superinverted state such that the p-n product in the space-charge region exceeds n_i^2. Such superinversion is maintained by hot-electron impact-ionization generation of holes. This is due to the large oxide voltage causing majority carriers, tunneling from the metal, to emerge as hot electrons in the semiconductor. This excess hole-generation current is balanced by the back diffusion of holes to the bulk, by recombination in the space-charge region, and by hole leakage to the metal, as shown in Fig. 1 [1]-[4].

Previous work has reported the use of optical generation, minority-carrier current injection, and applied voltage to produce switching of the device from the low-current to the high-current state [1]-[6]. In this letter, we report the use of a charge packet of minority carriers to cause switching of the device. By using this charge control method, new regions of operating variable space can be reached, and the properties of the device in CCD structures are revealed.

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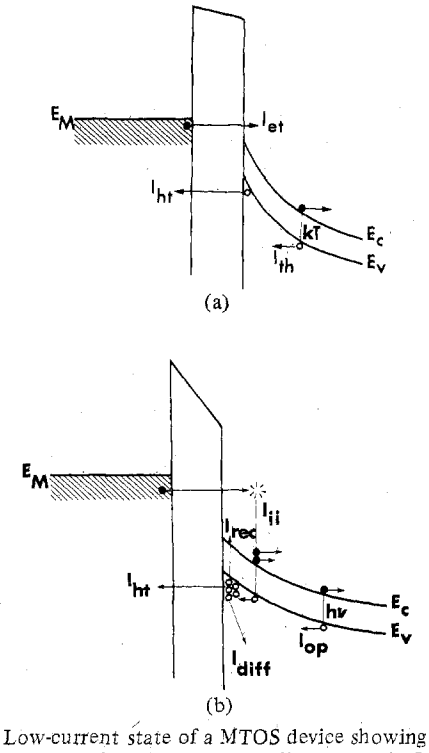

Fig. 1. (a) Low-current state of a MTOS device showing principal current components: I_{et} electron tunneling current, I_{ht} oxide hole transport current, and I_{th} thermal generation current. (b) High-current state of a MTOS device showing additional current components: I_{ii} impact ionization current, I_{rec} recombination current, and I_{diff} back hole diffusion current.

II. DEVICE FABRICATION

For the experiment, the layout shown in Fig. 2 was designed and fabricated. The experiment consists of a three electrode and p^+-n diode input structure, and an adjacent MTOS junction.

An n-type (100) silicon wafer was cleaned and a 2000-Å diffusion mask oxide was grown in steam at 900°C. This lower temperature was found to significantly improve the minority-carrier lifetime in the fabricated devices. The input diode was formed by a boron diffusion from a spin-on source at 1050°C for 75 min. The wet oxide mask was stripped and a thicker (~3000-Å) oxide was regrown in steam at 900°C. The n^+ channel stop was formed by a phosphorous diffusion from a spin-on source at 1000°C for 60 min. This phosphorous diffusion also serves as an impurity getter for minority-carrier lifetime improvement [7].

Gate oxide windows were opened and the gate oxide was

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grown in dry oxygen at 1000°C for 80 min, followed by an *in situ* N_2 anneal for 70 min. A forming gas (95-percent N_2, 5-percent H_2) anneal at 400°C was also performed. Tunnel oxide windows were wet-etched by BOE in the gate oxide, and the tunnel oxide was grown in dry oxygen at 800°C for 11 min, followed by an *in situ* N_2 anneal for 10 min. This process yields high-quality tunnel oxides [8].

Aluminum electrodes were then formed using a shadowed evaporation technique [9], yielding interelectrode gaps approximately 0.75 μm in width. Following the electrode definition and backside aluminum deposition, the wafer was given a post-metallization anneal in N_2 at 400°C for 10 min.

From small-signal capacitance-voltage (CV) measurements, the gate oxide was found to be 550 Å thick and had an inversion-layer-formation threshold voltage of −2.0 V. Using a pulsed C-t technique, a dark current of ~11 nA/cm^2, corresponding to an average minority-carrier lifetime τ_p of 8 μs, was measured. A CV extrapolation technique [10] yielded a tunnel oxide thickness of 33.4 Å ± 0.5 Å, the fractional angstroms reflecting on the measurement process, not the oxide.

III. DEVICE OPERATION AND RESULTS

To form a charge packet Q_{in} for injection into the MTOS junction, a voltage of −4.0 V is applied to V_{XI} and a voltage V_{MW}, larger than V_{XI}, is applied to the metering-well electrode. The input diode is then pulsed from −5 V to zero and then back to −5 V to perform a "fill and spill" operation [11]. The charge-packet size formed by this technique is given by

$$Q_{in} = C_{ox}(V_{MW} - V_{XI})$$

where C_{ox} = 41 pF is the gate oxide capacitance of the metering well.

The charge packet is injected into the MTOS junction by turning off V_{XI}, and applying $V_{XO} = -4.0$ V, $V_{TO} = -3.5$ V, and then ramping V_{MW} to zero at 0.25 V/μs, as depicted in Fig. 3. The transient MTOS device current (which to a good approximation is the electron tunneling current) is measured by a Keithley model 610C electrometer and displayed on an oscilloscope. A multiple-exposure photograph showing the transient device current is shown in Fig. 4.

For Q_{in} less than 630 pC, the transient current slowly decays (with a time constant of approximately 150 ms) because the excess inversion-layer charge gives rise to a recombination and divergence of minority-carrier current in the space-charge region. The major contribution to hole flow divergence is the larger-than-steady-state oxide voltage drop, which results in excess hole transport through the oxide. For Q_{in} greater than 630 pC, the impact-ionization generation of holes is greater than the oxide hole leakage rate, resulting in a buildup of inversion-layer charge and oxide voltage drop, and the transient current grows to the high-current state. The time to switch into the high-current state is a function of the initial inversion-layer charge, and is typically 10–100 ms. This slow charging time constant is due to the low impact-ionization probability of hot electrons in the 2.5-eV energy range.

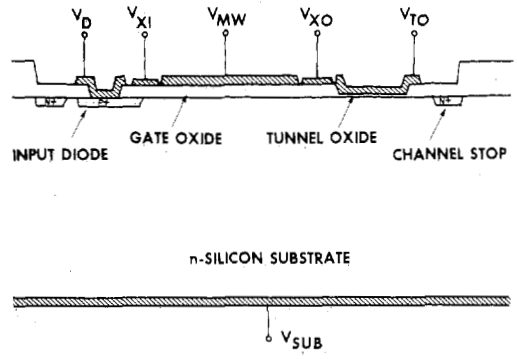

Fig. 2. Cross section of the experimental device structure.

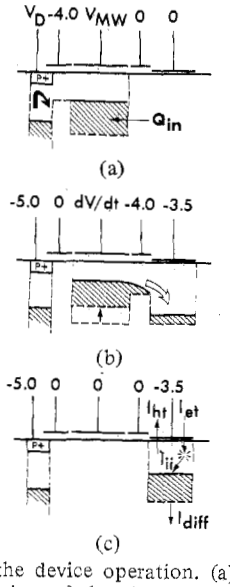

Fig. 3. Depiction of the device operation. (a) Charge-packet formation cycle. (b) Injection of the charge packet into a MTOS junction. (c) Transient response of a MTOS junction.

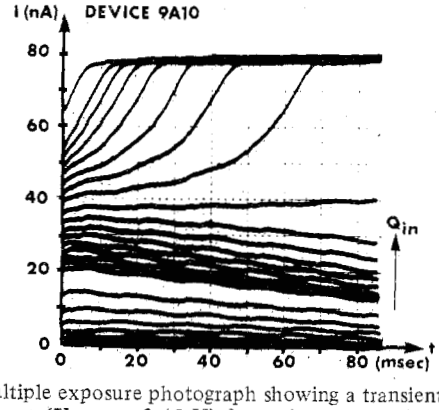

Fig. 4. Multiple exposure photograph showing a transient MTOS junction current (V_{TO} = −3.45 V) for various sizes of injected charge packets: the packet is injected at t = 0. V_{MW} is incremented by −1.0 V in the range −12 V to −22 V, except between −18 and −21 V, where V_{MW} is incremented by −0.2 V. The relationship between injected charge-packet size and V_{MW} is defined in text. Waveform ripple is due to a residual 60-Hz noise in the measuring circuit.

IV. CONCLUSIONS

In essence then, this charge-packet-initiated switching of the MTOS junction behaves as a charge-packet threshold detector, with a response time in the 100-ms range. We are presently making careful measurements of the transient current as a function of oxide voltage and time, to calculate oxide hole transport and hot-electron impact-ionization currents. The results of more detailed measurements and calculations of these processes will be published elsewhere.

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