Optoelectronic Devices for Unbiased Microwave Switching

J.L. Freeman, S. Ray, D.L. West, and A.G. Thompson

Boeing High Technology Center
P.O. Box 3999, M/S 7J-56, Seattle, WA 98124-2499

***Abstract*—Microwave switches needing no electrical bias are desirable in some environments. We present results from two devices: a surface-depleted, gateless, optical FET; and a FET controlled by an integrated photovoltaic diode. Insertion losses of 3 dB and isolations of 20 dB are obtained up to 5.6 GHz with an optical power of 1 mW.**

I. Introduction

METAL wires connecting microwave switches can perturb surrounding radiation, constrain designs, and lead to pickup and coupling between elements. Optical energy can also switch microwave signals and eliminate the metal bias lines. The optical fiber which delivers the switching signal is small, lightweight, EMI-immune, and virtually transparent to the microwave signals around it. One application requiring such a device is optically reconfigurable antennas [1-2].

For such applications, the device must meet many requirements. Key is good switching with no electrical bias or power. Since reconfigurable antennas such as that proposed in [1] can have many elements, the optical power needed per switch should be very small—certainly less than 1 mW. In addition, the large number of elements makes hybrid switches impractical. Ideally, the switch should have I-V curves that are linear and symmetrical around zero, have no "offset-voltage" before the linear region, and work to at least one volt before saturating. A response to 800-900 nm light also makes system design simpler, since LEDs and high-power lasers are more efficient and available in that region. Finally, the optically active area should be large—at least 20 μm and preferably 50 μm in diameter—to ease alignment with fiber optic inputs.

Existing devices cannot simultaneously meet these criteria. Simple III-V photoconductors, for example, have gains of only 10-20, thus requiring many milliwatts to achieve impedances below 50Ω [3]. A PIN diode drops in impedance when illuminated but needs bias to operate effectively [2]. Phototransistors and photodarlingtons have high gain but high capacitance that limits their utility in the microwave band. While optical effects in FETs have been extensively studied [4], most are evaluated as biased detectors. In particular, optically triggered FETs have not previously been designed and optimized for unbiased microwave switching.

We have developed two integrated devices addressing the above requirements: an interdigitated, surface-depleted optical FET (surface OPFET) and a FET integrated with a photovoltaic cell (PV/FET). Unbiased operation and low optical power were the most important criteria; switching speed was expendable.

II. Surface OPFET

The first device exploits the optical sensitivity of an air-GaAs interface [5-7] (see Figure 1). When the interdigitated area is illuminated, photogenerated holes accumulate at the surface, reducing the built-in surface depletion [8]. As such, the device is essentially a surface-depleted optical FET in which the gate is replaced by the optically sensitive interface. Unlike a traditional photoconductor, the gain is a function of optical power.

The device structure is like a simple MESFET without a gate. For ease of experimentation, the thickness of the channel layer is optimized by measuring the DC I-V curves between short etch cycles. A

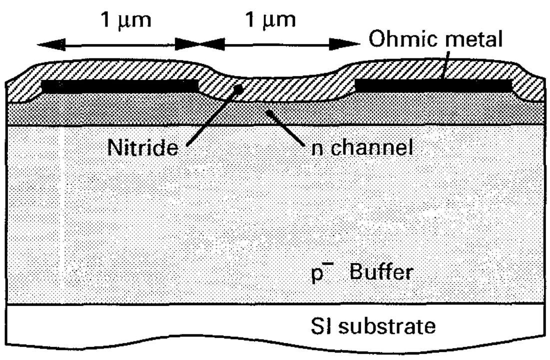

Figure 1. Cross-section of surface-depleted optical FET switch. Fingers are interdigitated; typical active area is 20 x 20 μm.

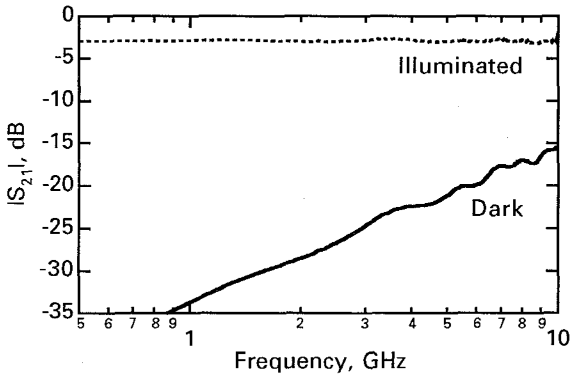

Figure 2. Loss $|S_{21}|$ through surface OPFET switch in illuminated (1 mW optical power) and dark states.

subsequent silicon nitride coating minimizes degradation of the surface state due to the environment. The coating needs to set and stabilize the surface-state density at a *high* level, unlike typical passivation layers. Although we have had good results with this nitride coating, further lifetime and surface studies clearly are needed.

The etching of the channel allows tradeoffs in the device performance. Devices etched longer have thinner channels, higher dark and illuminated impedances, faster responses, and lower gains. If the entire doped channel is removed, the dark impedance is very high, but gain is low [9]. For these switches, though, high dark resistance is wasteful, since the dark *impedance* is limited by device capacitance. It is more useful to lower both illuminated and dark resistances until the dark resistance is near the reactive impedance at the frequency of interest. At the other extreme, no etching, the gain is very high but the dark resistance is far too low.

The high gains in this gateless optical FET result from the long lifetimes of the holes at the GaAs surface [10]. The resulting time for the switch to turn off after illumination is much longer than the bulk recombination time (nanoseconds) or the transit time (picoseconds). Qualitatively, the band bending at the surface separates the holes accumulated at the surface from the electrons. Both surface traps and band bending away from the surface slow recombination, increasing gain and slowing switching. For the lower gain devices, switching times are less than a microsecond. The devices that are most sensitive optically can exhibit switching times of milliseconds.

Microwave performance is measured on wafer with coplanar probes. The switch is designed into the center conductor of a coplanar waveguide transmission line. No external biases or bias tees are used. A scalar network analyzer measures $|S_{21}|$ vs frequency; switching time was measured with an HP 70820 Microwave Transition Analyzer (MTA), which measures the envelope of the RF transient. The switching time was considered to be the time for the signal transmitted through the switch to drop to –20 dBc when not capacitance limited.

Optically, a fast 850 nm laser was driven fully on and off by a square wave generator whose repetition rate was chosen to show all of the fall-time transient. The same source was used without modulation for $|S_{21}|$ vs RF frequency measurements. The optical beam was then focused through a microscope lens to the on-wafer device.

Figures 2 and 3 show the frequency and switching properties of a switch with relatively fast response and moderate gain. The insertion loss is 3.0 ± .2 dB, indicating a simple 41 Ω resistance; the isolation is above 20 dB to 5.6 GHz, indicating a 29 fF capacitance. The switching time at 4 GHz is about 1.5 μs but less than 0.5 μs at 1 GHz, where capacitance is not the limiting factor. Devices structurally similar but with lower parasitic capacitances have shown isolations greater than 20 dB to 10 GHz while maintaining an insertion loss less than 3 dB at 1 mW.

A typical response of a high gain switch from the same wafer as Figures 2 and 3 is shown in Figure 4. The falltime is now nearly 1.5 ms but the insertion loss is more than 1 dB lower. The optimum tradeoff of gain and speed depends on the detailed application needs.

Despite the sensitivity to channel thickness, repeatable performance has been obtained over many wafers and device designs. Unlike traditional photoconductors, the device is optically nonlinear,

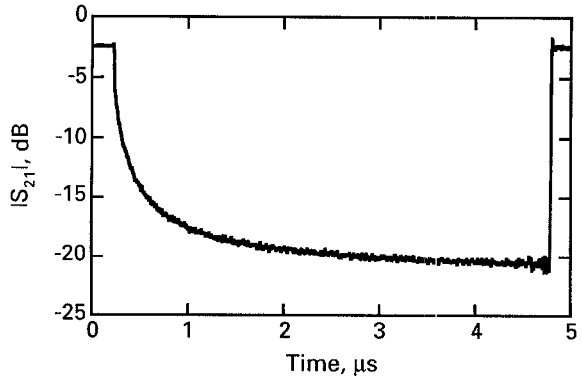

Figure 3. Transient response of moderate-gain surface OPFET with 4 GHz RF signal.

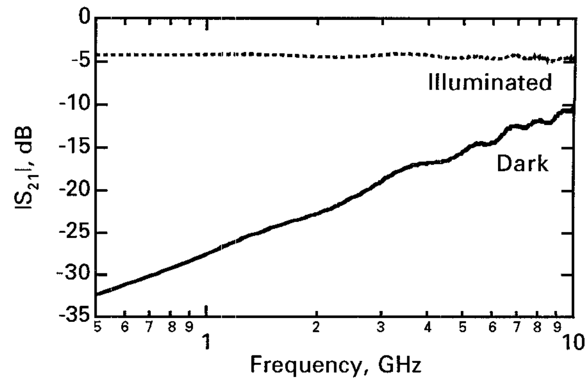

Figure 5. Loss $|S_{21}|$ through PV/FET switch in illuminated (1 mW optical power) and dark states.

so larger area devices can give lower resistances, though still at the price of higher capacitance. A 50 μm diameter switch, for example, has exhibited an insertion loss less than 1 dB and an isolation of 20 dB to 1.4 GHz.

III. PV/FET Switch

A second optoelectronic switch integrates photovoltaic diodes with GaAs FETs. In the dark, the photodiodes generate no voltage, and the enhancement-mode device remains off. When illuminated, the photodiodes generate an open-circuit voltage into the high impedance gate and turn the FET on. Turn-on of the gate-source diode limits the gate voltage in practice. When the light is turned off, leakage or a gate-source load discharges the gate.

Figure 5 shows the switching vs frequency of this switch. The insertion loss of 4.2 dB is expected from the 65Ω DC resistance of the switch when illuminated. Isolation is limited by the 56 fF capacitance, both of the depleted FET and photodiodes. As with other FET-based switches, isolation and insertion loss are traded by varying the gate width.

Figure 6 shows the transient response of the switch of Figure 5. The fall-time is less than 10 ns, fast enough for nearly all switching applications. Gates without loads give the most sensitive switches, but with switching times of micro- to milliseconds, depending on the exact gate leakage. When all loads are removed from the device of Figure 5, for example, the falltime increases to 1.3 ms.

Because little current is drawn by the gate, this switch is also optically nonlinear. Figure 7 shows the change in the insertion loss with optical power of two FET switches: one, the switch characterized in Figures 5 & 6; the other, the same switch with gate loads removed. As long as the photogenerated current is greater than the load or leakage, the switch stays on; for lower photocurrents, the photovoltage drops and the FET begins to turn off. With no load, extremely small optical powers suffice to keep the device on.

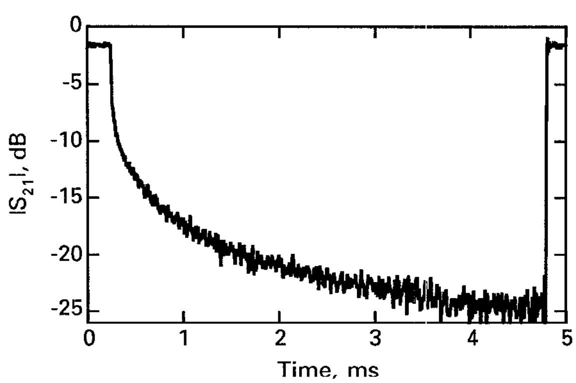

Figure 4. Transient response of high-gain, surface OPFET with 1 GHz RF signal.

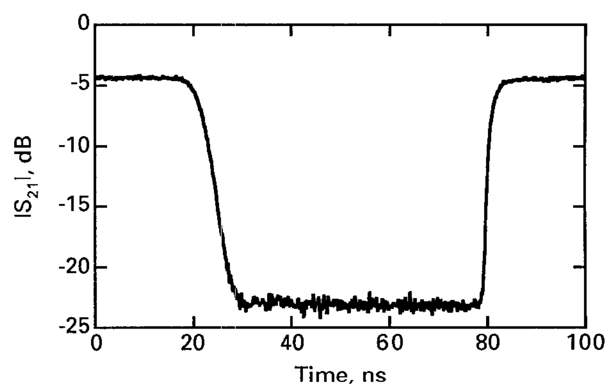

Figure 6. Transient response of the PV/FET switch with gate load and 2.0 GHz RF signal.

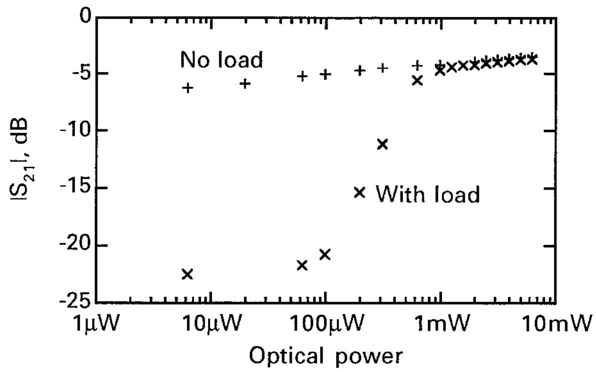

Figure 7. Optical nonlinearity of the PV/FET switch. Loss increases as gate discharge exceeds photocurrent.

Improved performance is possible in many ways. Both the FETs and the photodiodes can be optimized for better switching and more efficient photogeneration. One convenient advantage over the surface OPFET is the ease of trading gain and sensitivity for a given application. The surface OPFET requires a process adjustment while the PV/FET needs only a layout change.

IV. Summary

We have described two simple microwave switches controlled by a weak optical beam. They are suitable for connecting microwave elements where electrical bias is not possible. The low optical power and integrated form are especially necessary in applications where hundreds or thousands of switches may be driven by a small number of powerful optical sources or by many LEDs.

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