Field-Effect Transistor Self-Electrooptic Effect Device: Integrated Photodiode, Quantum Well Modulator and Transistor

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Abstract—**We propose and demonstrate the integration of a photodiode, a quantum-confined Stark effect quantum well optical modulator and a metal-semiconductor field-effect transistor (MESFET), to make a field-effect transistor self-electrooptic effect device. This integration allows optical inputs and outputs on the surface of a GaAs-integrated circuit chip, compatible with standard MESFET processing. As an illustration of feasibility, we demonstrate optical signal amplification with a single MESFET.**

QUANTUM well modulators based on the quantum-confined Stark effect (QCSE) are low-energy, electrically-driven devices compatible with electronics in materials and voltages and with laser diodes in wavelengths and power levels [1]. To make a device or system with optical inputs and outputs, we can combine photodetectors and other circuitry with these modulators; this is the principle of the self-electrooptic effect device (SEED) [2] in its most general form [3]. Many such devices have been proposed, with circuits including simple resistor biasing [2], biasing through another photodiode [2], [4], and with bipolar phototransistors [3], [5], although we are not currently aware of any other successful demonstration of integration with transistors. In this paper, we propose and demonstrate a scheme for the integration of field-effect transistors (FET's) with photodiodes and QCSE modulators to make field-effect transistor SEED's (F-SEED's). This scheme can be used in principle to make FET circuits of arbitrary complexity with arbitrary choice of optical inputs and outputs at any points in the circuit.

One other elegant scheme has been proposed and demonstrated that integrates FET and modulation functions by using the phase-space absorption quenching (PAQ) mechanism directly in a quantum well FET channel [6]. This PAQ mechanism is potentially well suited for waveguide modulators. The present scheme is, however, also compatible with two-dimensional arrays of light beams propagating perpendicular to the chip surface through "free-space" optics.

The concept in its simplest implementation is illustrated schematically in Fig. 1. As shown in Fig. 1(a), a reverse-biased photodiode is connected to the gate of an FET so that, when light shines on the photodiode, it reduces the gate voltage on the FET, tending to turn it off, thereby providing an optical input to FET circuitry. The output from an FET (in this simple illustration, the same FET as used for the input) can then drive a quantum well modulator, thereby modulating the power light beam to give the optical output.

In Fig. 1(b), we show the concept of the integration scheme. A quantum well modulator diode is grown in which an FET can be fabricated in the top layer of the diode itself. For this demonstration, this top layer is simply n-doped GaAs, so that conventional MESFET's can be made. Other transistor designs could be used. As the transistor is operated, its drain voltage will change, and hence so also will the voltage across the quantum well n-i-p diode region beside the drain. Consequently, a light beam passed through the quantum well diode, as shown in Fig. 1(b), will be modulated, hence providing an optical output directly from the FET. Importantly, the modulation depth can be large (e.g., > 2:1) even for light beams propagating perpendicular to the surface. We can also separately use another part of the n-i-p diode as a photodetector elsewhere on the chip, as shown for the specific case where it drives the output FET.

The layer structure for the demonstration device was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The aluminum mole fraction x is ~ 0.29 in all $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layers. The first layer grown is a 1500 Å thick GaAs buffer layer doped $\sim 10^{18}\ \mathrm{cm}^{-3}$ p-type. This is followed by a 1 μm thick $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer, doped $\sim 10^{18}\ \mathrm{cm}^{-3}$ p-type. Then 67 pairs of quantum well layers are grown, all without intentional doping, each pair consists of a 95 Å thick GaAs layer followed by a 55 Å $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer. Then a 3300 Å thick GaAs layer, doped $\sim 10^{17}\ \mathrm{cm}^{-3}$ n-type, is grown. The final layer is 500 Å thick GaAs doped heavily n-type to $2 \times 10^{18}\ \mathrm{cm}^{-3}$.

The device fabrication is a relatively standard MESFET process. First the source and drain contacts were formed, approximately 6 μm apart, on the top GaAs layer. Then the individual field-effect transistors (and any mesas to be used as diodes) were isolated from one another by a mesa etch through the n-doped GaAs layers. A gate mask was formed to leave a nominally 2 μm wide strip exposed approximately centered between the source and drain. Then this region was chemically etched down through the heavily n-doped GaAs layer into the lightly n-doped GaAs layer to a depth of approximately 1000 Å to adjust the threshold of the transistor. Finally, the gate metallization was deposited and the gate mask was lifted off.

Wires are then attached to the source, gate, and drain pads,

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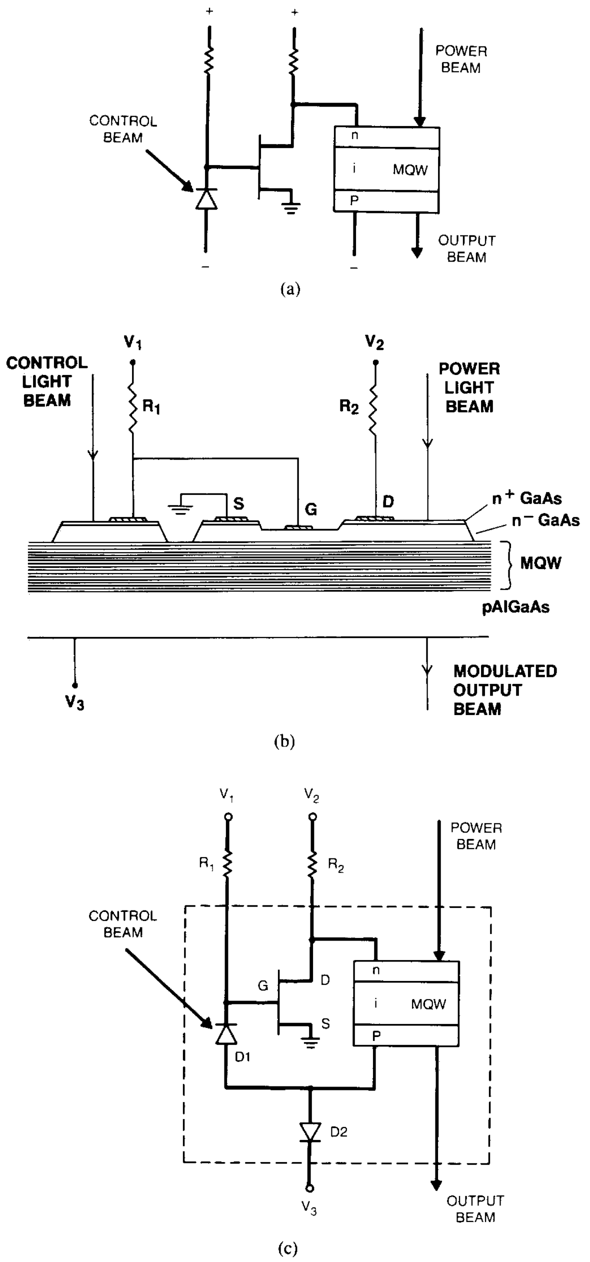

Fig. 1. (a) Simplified circuit schematic of integration of photodetector, field-effect transistor, and quantum well modulator, configured as an optical signal amplifier. (b) Schematic of layer structure and interconnections. *S*, *G*, and *D* refer to the source, gate, and drain of the MESFET, respectively. (c) Actual circuit schematic of the device as demonstrated. Only the region within the dashed box was integrated here. In operation, the contact to the p-layer was not direct, as shown in (b) above, but indirect through another, forward-biased diode, *D*2, elsewhere on the chip. Actual values used for the demonstration were $V_1 = 0.1$ V, $V_2 = 10$ V, $V_3 = -2.75$ V, $R_1 = 1$ MΩ, $R_2 = 10$ kΩ.

and the whole structure is epoxied, processed side down, to a transparent sapphire. Finally, the GaAs substrate and the GaAs buffer layer are removed under the devices of interest with a selective etch.

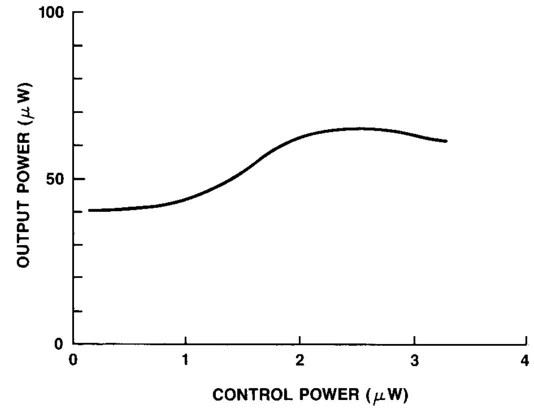

Fig. 2. Optical input/output characteristics for the three-terminal optical amplifier circuit of Fig. 1. Wavelength—856.1 nm. Power beam—450 μW input.

The actual circuit used for the demonstration is shown in Fig. 1(c). Contact to the buried p-layer was made using a diode mesa in forward bias. Only the portion within the dashed box was integrated here; the resistors and connections were external. This circuit operates as an optical amplifier. A weak light beam shines on the photodiode, generating a photocurrent that results in a voltage at the transistor gate. This starts to turn the transistor off, raising the drain voltage and hence increasing the reverse bias voltage across the modulator. Consequently, the absorption of the modulator changes. For the specific wavelength used here (chosen to be near the peak of the heavy hole exciton absorption at zero reverse bias), this gives an increase in optical transmission. A resulting optical input/output characteristic is shown in Fig. 2, showing that optical signal gain is possible with such a device. For these particular parameters, the device shows a small signal gain of ~25 near 1.5 μW and a large signal gain of ~12 between 0 and 2 μW. This demonstration also shows that there is a set of biasing voltages under which all of the parts of the device can work simultaneously.

As with all integrations of different components, there are some tradeoffs. The FET here will have some back-gating from the buried, biased p-layer, although this is a relatively minor effect. It will also have some additional capacitance to ground (compared to FET's on insulating substrates) because of this p-layer; however, most of this appears as drain capacitance at the output stage (i.e., the optical modulator), and hence is not functionally parasitic. With the simple FET structure shown here, there will be some additional absorption loss for the light beams (~30 percent for the specific design here) because of the optical absorption of the GaAs layer at the operating wavelength (~850 nm). The FET must also operate at sufficiently high voltages (e.g., 5–10 V) to drive the modulator. A significant weakness of the present demonstration is that the GaAs substrate has to be removed under the whole structure, leaving a potentially fragile structure with poor thermal properties. This could be overcome by combining the present structure with an integral dielectric mirror, as has been successfully demonstrated with a modulator structure [7], thereby retaining the substrate and increasing the modulator contrast by passing the light twice through the quantum wells.

The demonstration here is only a proof of principle. Although the performance of the individual detector, transistor, and modulator should not be severely compromised by the interaction, a proper assessment of system performance must await full integration, including the load resistors, since external parasitics otherwise dominate performance.

In conclusion, we have demonstrated that it is possible to integrate photodetectors and quantum well modulators with FET's while retaining standard FET processing. This allows us to contemplate electronic circuitry with many optical inputs and outputs. Importantly, the resulting optical input and output "pads" could be small (e.g., < 10 μm) and could be accessed with two-dimensional arrays of light beams. Although only a simple system was demonstrated here, the possibility exists for more complex functionality between optical inputs and outputs by including more transistor circuitry. Consequently, such a scheme may enable us to use electronics and optics each to their best advantage by allowing us to make the choice of the best point in a system to go from one to the other.

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