

developed to explain our experimental observations.

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## Very high frequency GaAlAs laser field-effect transistor monolithic integrated circuit

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A very low threshold GaAlAs buried heterostructure laser has been monolithically integrated with a recessed structure metal-semiconductor field-effect transistor on a semi-insulating substrate. At cw operation, the device has a direct modulation bandwidth of at least 4 GHz.

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Monolithic integration of injection lasers with various electronic devices has been reported recently in the III-V compound systems.<sup>1-4</sup> Fabrication of metal-semiconductor field-effect transistors (MESFET's), Gunn devices, bipolar transistors, and metal-insulator-semiconductor field-effect transistors (MISFET's) with laser diodes and photodetectors to form integrated optoelectronic circuits possesses many advantages. In addition to small size, low fabrication cost, and high reliability, significant improvements can be gained in terms of speed and noise performance due to the reduction of parasitic reactances. A crucial factor in the design of integrated optoelectronic circuits is the fabrication of a low threshold current laser. This is important in terms of increasing the circuit reliability due to low heat dissipation, and extending the frequency bandwidth of the laser resulting from higher current levels which can be achieved.

We have recently reported the development and fabrication of a buried heterostructure (BH) laser on a semi-insulating GaAs substrate<sup>5</sup> with very low threshold current (8–15 mA), high differential quantum efficiency (55%), and single-mode operation. In the letter reported here we have integrated this laser with a recessed structure MESFET<sup>6</sup> to form a monolithic integrated optoelectronic circuit. The bandwidth of this device under direct modulation exceeds 3.5 GHz with an optical modulation depth up to 70%. This makes it an attractive building block for high-speed communication applications such as in transmitters, repeaters, and multiplexers.

A schematic view of the device is shown in Fig. 1. The

laser is fabricated in a similar way to the one described in Ref. 5. The fabrication steps which were used to realize the device are as follows. Epitaxial layers are grown on a semi-insulating GaAs substrate in the following order: FET channel layer (*n*-GaAs), FET contact layer (*n*<sup>+</sup>-GaAs), lower cladding layer (*n*-GaAlAs), active layer (undoped GaAlAs), and an upper cladding layer (*p*-GaAlAs). Mesas are then etched down to the middle of the *n*<sup>+</sup>-GaAs contact layer to form the laser waveguides. The crystal is then reintroduced into the epitaxial growth system and a *p*-GaAlAs blocking layer is grown, followed by an *n*-GaAlAs burying layer. Contact to the lasers is formed by diffusing Zn through openings in a silicon dioxide mask followed by evaporation of chromium and gold. After etching gold, chromium, and silicon dioxide, a selective etchant is used to etch away the

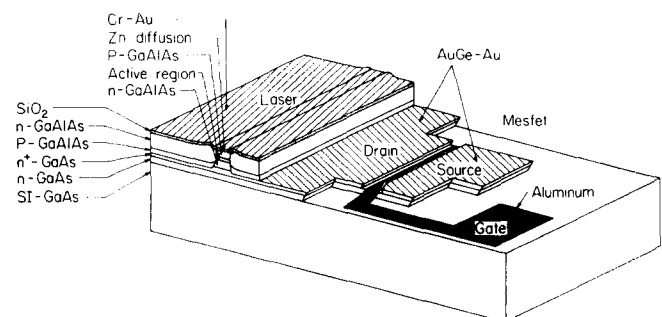


FIG. 1. Schematic diagram (not to scale) of the BH laser—MESFET integrated circuit.

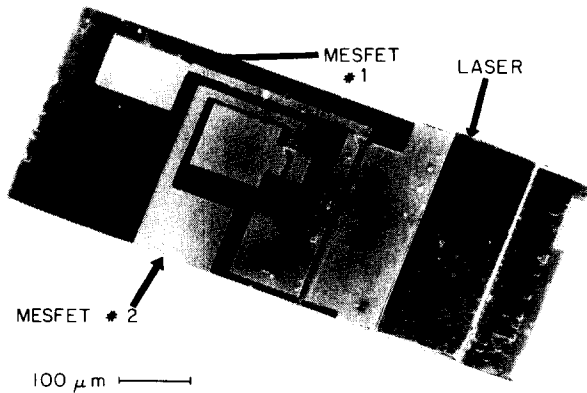


FIG. 2. SEM photograph of the device. MESFET #1 is the transistor which is active in the circuit. MESFET #2 is irrelevant for this study. The laser stripe is also indicated.

GaAlAs layers beside the laser mesa. To form contacts for the MESFET source and drain, Au-Ge and Au are deposited onto the wafer using lift-off. Transistor mesas are then defined by etching down to the semi-insulating substrate in the region surrounding the MESFET's. After patterning contacts for the source and drain, the contact metal is thermally alloyed to form ohmic contacts. The region where the gate metal is to be applied is next defined photolithographically. The wafer is then immersed in a slow etchant to etch the MESFET channel to the desired thickness. In order to monitor the thickness of the channel, the source and drain of a transistor are contacted through the photoresist layer using steel probes. When the saturation current of the channel reaches the desired value ( $\approx 50$  mA), etching is halted. To form the gate, aluminum is evaporated onto the wafer and lifted off. An scanning electron micrograph (SEM) photograph of the complete device is shown in Fig. 2.

The laser characteristics are similar to those described in Ref. 5. These include a typical threshold current of 20 mA and external differential quantum efficiency of 55% for a cavity length of  $300 \mu\text{m}$ . The MESFET's have a pinch-off voltage of  $\approx 6-7$  V and a transconductance of  $\approx 10$  mmho. The laser and MESFET are connected in series with a combined  $I-V$  characteristic as shown in Fig. 3.

The combination of a FET with a very low threshold laser on a semi-insulating substrate results in a very large modulation bandwidth—exceeding 3.5 GHz—for this device. The insert in Fig. 4(a) shows a schematic diagram of the high-frequency measurement setup. The integrated laser FET device was bonded to a  $50\text{-}\Omega$  microwave stripline package. Quiescent bias and microwave drives were applied to the gate of the FET through bias-T's as shown in this figure. The gate pad of the FET was terminated with  $50\text{-}\Omega$  which ensures a wideband match to the system—the measured input VSWR of the device is lower than 1.15 over the entire band from 0.1–4 GHz. Such wideband matching is not possible in a solitary laser diode. The modulated light output was detected with an avalanche photodiode (APD, BPW-28), whose microwave output signal was compared to the drive signal with a network analyzer (hp8410). The frequency re-

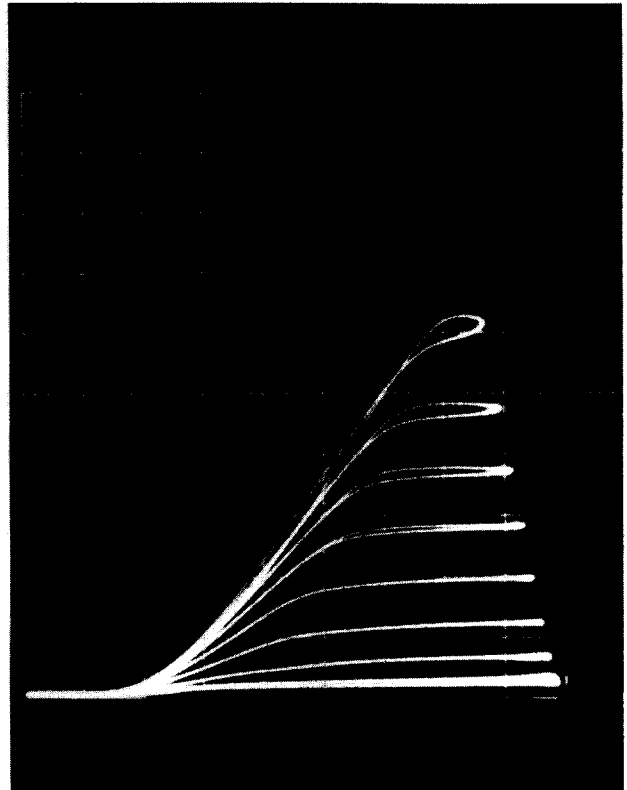
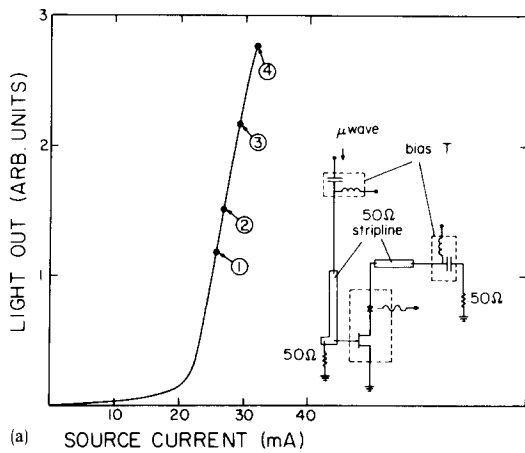
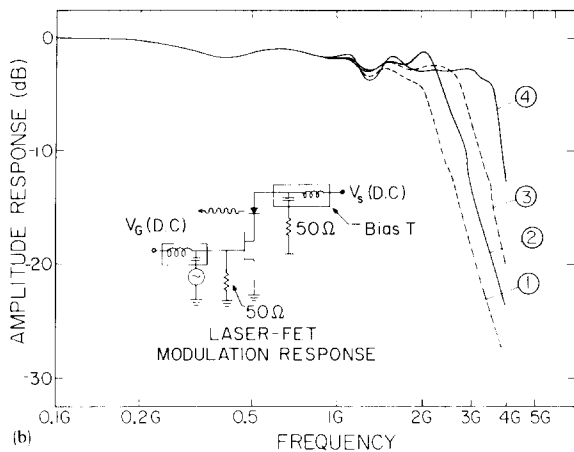


FIG. 3.  $I-V$  characteristic of the device where the laser and MESFET are connected in series. The top curve corresponds to  $V_g = 0$  V. Ver. is 10 mA/div, hor. is 1 V/div, gate voltage is 1 V/step.

sponse of the APD was precalibrated using both a picosecond dye laser and a GaAs laser excited by a step recovery diode, which is known to produce optical pulses of 15–30 ps.<sup>7</sup> The detection bandwidth of the APD was determined to be approximately 2 GHz by either method. The response at 4 GHz was down by about 20 dB. The detector response rolls off very rapidly beyond 4 GHz. Figure 4(a) shows the cw laser output as a function of source current. Determination of the modulation bandwidth of the device from the rise and fall time of the laser in response to a single excitation pulse is very unreliable because in pulse measurements, the laser can be easily driven into the nonlinear regime so that its rise and fall times do not correspond to the actual information carrying bandwidth.<sup>7</sup> Instead, cw sweep-frequency measurement was used. Microwave measurements were taken at various bias points shown on the light-current curve in Fig. 4(a), corresponding to the sweep-frequency response curves in Fig. 4(b). At a moderate bias current of 30 mA, which corresponds to  $\approx 1.5 \times$  laser threshold, the response of the device was flat up to 4 GHz. When the data in Fig. 4(b) were normalized by the APD response, one obtains the true response of the device, displaying the familiar relaxation oscillation resonance peak as shown in Fig. 5. These response curves were obtained at an optical modulation depth of  $\approx 35\%$ , and remained substantially unchanged up to a level of 60–70%. The impressive flatness of the unnormalized response through 4 GHz [Fig. 4(b)] illustrates that the relaxation oscillation of a laser can be equalized with a photodetector having an appropriate bandwidth and roll-off rate.



(a) SOURCE CURRENT (mA)



(b)

FIG. 4. (a) cw laser output as a function of source current. Microwave measurements were taken at various bias points shown on this curve, corresponding to the sweep-frequency responses in (b).

The excellent modulation characteristics of the laser-FET can be largely attributed to the excellent quality of the laser itself and its fabrication on a semi-insulating substrate, which results in a substantial reduction in the parasitic capacitance of the laser compared with lasers fabricated on conductive substrate. Given the multi-GHz bandwidth of MESFET's the laser becomes the bandwidth-limiting element of any optoelectronic integrated circuit involving lasers and FET's. The most damaging parasitic element in high-frequency operation—the laser parasitic shunt capacitance—can be substantially reduced in the integrated structure by virtue of a minimum size contact pad and its fabrication on a semi-insulating substrate. Analysis<sup>8</sup> shows that as long as the parasitic capacitance is below 5 pF, the modulation bandwidth of the laser will not be compromised for fre-

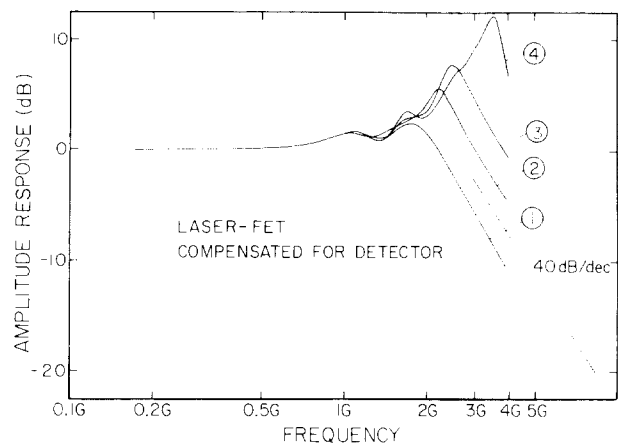


FIG. 5. Sweep-frequency response of the laser-FET as in Fig. 4(b), normalized by the detector response.

quencies up to 5 GHz. The parasitic capacitance of these BH lasers on semi-insulating substrate, obtained by microwave *s*-parameter measurements, was estimated to be between 4–5 pF, compared with  $\approx 10$  pF for BH lasers on conductive substrate and much higher values in channelled substrate planar (CSP) or similar types of lasers. This may account for the observed dip in the modulation response of CSP lasers<sup>9</sup> whereas such dips are of lower magnitude in BH lasers and not observed at all in our lasers on semi-insulating substrate.

In conclusion, a low threshold BH laser has been integrated monolithically with a recessed structure MESFET on GaAs semi-insulating substrate. The circuit exhibits a direct modulation bandwidth exceeding 4 GHz.

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