Monolithic integration of a very low threshold GaInAsP laser and metal-insulator-semiconductor field-effect transistor on semi-insulating InP

U. Koren, K. L. Yu, T. R. Chen, N. Bar-Chaim, S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 21 December 1981; accepted for publication 19 January 1982)

Monolithic integration of 1.3-μm groove lasers and metal-insulator-semiconductor field-effect transistors (MISFET) is achieved by a simple single liquid phase epitaxy (LPE) growth process. Laser thresholds as low as 14 mA for 300-μm cavity length are obtained. MIS depletion mode FET's with *n* channels on LPE grown InP layer show typical transconductance of 5–10 mmho. Laser modulation by the FET current is demonstrated at up to twice the threshold current.

PACS numbers: 42.55.Px, 42.82. + n, 85.40.Gn

The monolithic integration of optical and electronic devices on a single semiconductor cyrstal[1] is potentially important in high-speed optical fiber communication systems. Monolithic integration of several electronic devices such as metal-semiconductor field-effect transistors and bipolar transistors with laser diodes have been demonstrated with the GaAs/GaAlAs double heterostructure (DH) lasers.[2–5] So far, to our knowledge, no similar work has been reported for the GaInAsP/InP system where the laser wavelength (1.1–1.6 μm) is optimal for optical fiber transmission.

In this letter we report a monolithic integration of high performance GaInAsP/InP laser and InP, *n*-channel, depletion mode, metal-insulator-semiconductor field-effect transistor (MISFET) on semi-insulating (SI) InP substrate. This integration is achieved with a remarkably simple structure utilizing a single growth liquid phase epitaxy.

The groove laser used for this work is similar to a laser recently reported by us.[6] The active region of this laser is a crescent shaped buried optical waveguide. Lateral electrical confinement is obtained by the surrounding SI InP material. This structure results in a simple and high performance laser. Its low threshold cw operation enables us to directly modulate light output with the MISFET drain-source current with no additional biasing. One aspect in which the present laser differs from the laser reported earlier[6] is that all the three LPE grown layers (see Fig. 1) are of *n*-type material, and the laser diode is obtained by the laterally Zn diffused junction. The first undoped *n*-type InP layer is also used to provide the *n* channel for the MISFET.

A schematic cross section of the device is shown in Fig. 1 and a scanning electron microscopy (SEM) photomicrograph of the laser is shown in Fig. 2. The fabrication process of this device begins with the chemical vapor deposition (CVD) of Si_3N_4 on the InP substrate. Then, grooves are made in the [011] direction of the SI InP substrate through 2.5-μm stripe openings. The Si_3N_4 is selectively removed from one side of groove leaving 100-μm Si_3N_4 stripes on the substrate. These stripes act as masks on which no growth occurs during

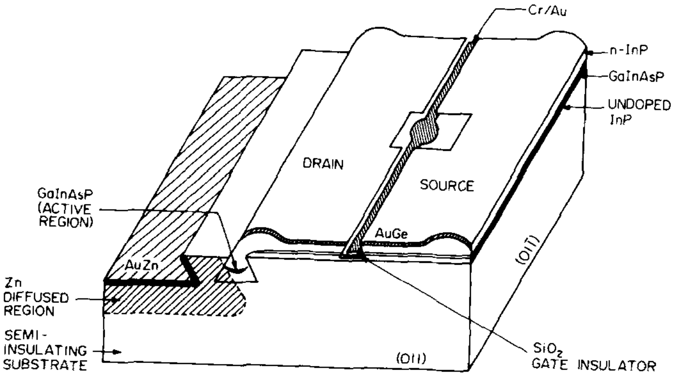

FIG. 1. Schematic diagram of the integrated device.

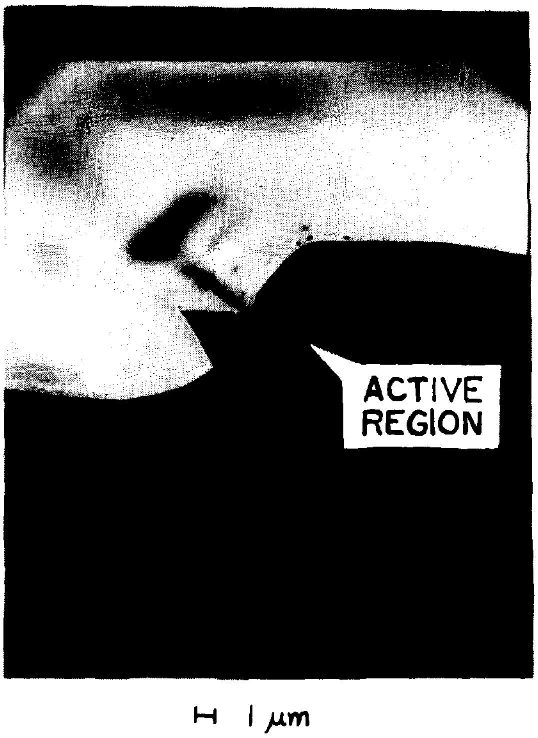

FIG. 2. SEM picture of the groove laser.

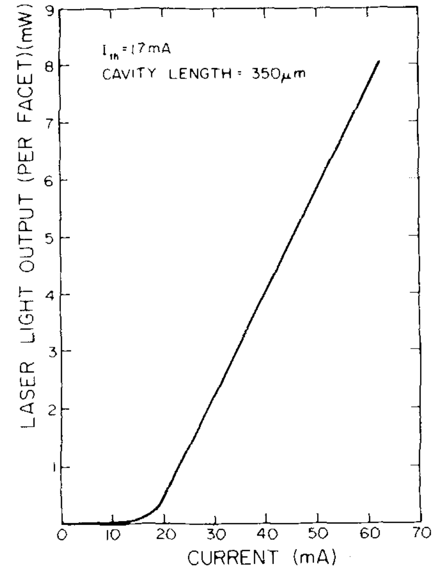

FIG. 3. *L-I* characteristics of the integrated laser for pulsed operation.

epitaxy. Three LPE layers are grown on the grooved wafer: an undoped InP (background electron concentration in 4–$9\times10^{16}\,\text{cm}^{-3}$), a thin ($\sim0.2\,\mu$m) undoped quaternary GaInAsP layer, and *n*-type InP ($2\times10^{18}\,\text{cm}^{-3}$, Sn doped) layer.

Following the LPE, a new Si_3N_4 layer is deposited and windows for diffusion are opened. Through these windows the wafer is etched, and a Zn diffusion which penetrates the undoped LPE grown layer inside the groove (see Fig. 1) is performed. Then the AuZn/Au and AuGe/Au electrodes are deposited and photolithographically defined. The FET channel is defined by etching through the top two layers and into the undoped, first grown LPE layer, thus forming a recess structure (see Fig. 1). Gate insulation is achieved by 15 minutes of plasma treatment in oxygen, followed by CVD SiO_2 layer of $\sim$600-Å thickness. The gate electrode is made of a Cr/Au layer using a conventional lift-off technique. The recess etched for the FET channel is about 6 μm long and the gate electrode is 1.5 μm long. The wafer is thinned and cleaved to 300–400-μm (cavity length) chips. These chips are bonded upside up to copper heat sinks using conductive epoxy.

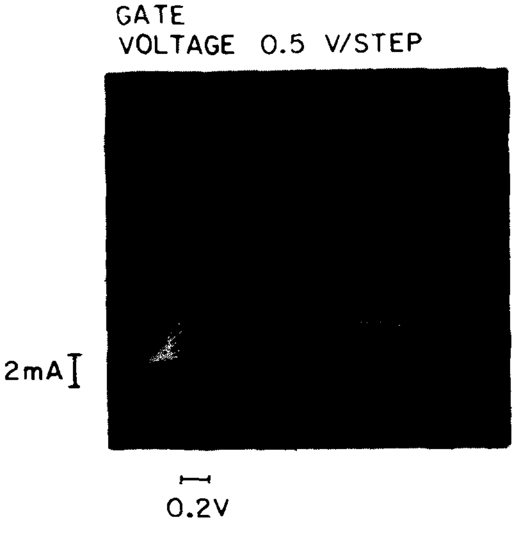

FIG. 4. *I-V* characteristics of the depletion mode InP MISFET.

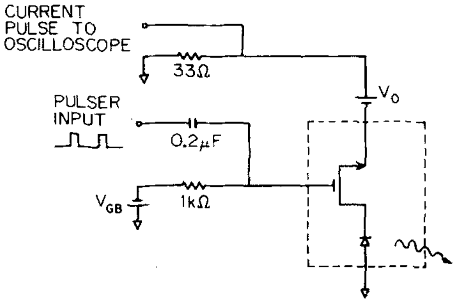

FIG. 5. Schematic diagram of the modulation test circuit.

The light/current characteristics of a laser are shown in Fig. 3 for pulsed operation. This laser has a pulsed threshold current of 17 mA and a cavity length of 350 μm. The lowest threshold current for these lasers is 14 mA, with 300-μm cavity length. The external differential quantum efficiency for both facets is 35%. Room-temperature cw operation of the lasers is obtained with threshold currents as low as 15 mA. The laser operates at 1.3-μm wavelength and has a single longitudinal mode at up to 1.4 threshold current. A single lateral mode operation is obtained when the active region width is less than 2.5 μm. The FET has a transconductance of about 5–10 mmho. The drain-source current at zero gate voltage (I_{DSO}) is controlled by the thickness of the channel and can be typically 15–40 mA with 3-V drain-source voltage. The I_{DSO} current does not always saturate completely at zero gate voltage but frequently saturates or shows negative resistance at $V_g < 0$. Typical curve tracer characteristics of the MISFET are shown in Fig. 4.

To demonstrate laser light modulation by the FET the test circuit shown in Fig. 5 is used. The laser is modulated by introducing 1.5-μs pulses through a high impedance to the FET gate terminal. The I_{DS} current response and the laser light output is shown in Fig. 6 with $V_0 = -4$ V and $V_{GB} = -5.5$ V. The laser light output is modulated on-off by the FET. At pinch-off, that is, before and after the pulse, the current is less than 10 mA which is well below the laser threshold current. During the pulse the FET conducts and I_{DS} values of about 2 I_{TH} are obtained. The light pulse rise time shown in Fig. 6 is limited by the Ge photodiode response time (100 ns) that is used here.

In conclusion, a high performance GaInAsP/InP 1.3-μm wavelength laser diode is integrated with a MISFET on a semi-insulating substrate using a simple single LPE growth process. Modulation of the laser light output by the FET is demonstrated.

This work is supported by the Office of Naval Research and the National Science Foundation (Optical Communication Program).

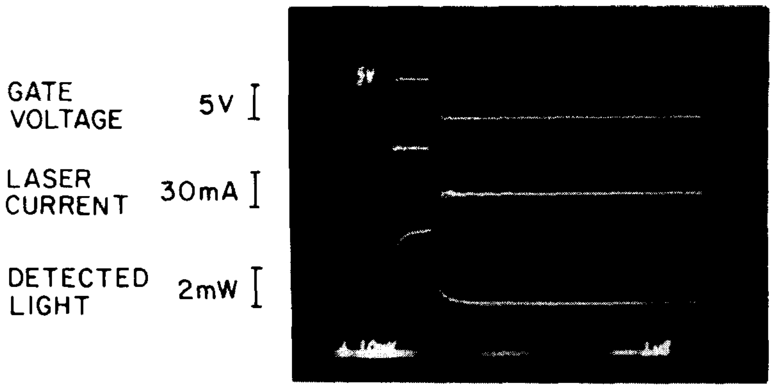

FIG. 6. Modulation of the laser output by external pulses applied to the gate terminal.

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Optical-thermal induced total internal reflection-to-transmission switching at a glass-liquid crystal interface

I. C. Khoo
Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48202

(Received 14 December 1981; accepted for publication 26 January 1982)

An intensity dependent change from a state of total internal reflection to transmission of an optical beam at a nonlinear glass-nematic liquid crystal interface is observed. The effect is attributed to optically induced molecular reorientation and thermal indexing, depending on the liquid crystal used.

PACS numbers: 61.30.Gd, 42.10.Qj, 42.65. – k

Recently, the subject of optical switching at a nonlinear interface has received considerable attention.[1–4] In particular, the change from a state of total internal reflection to a transmission state due to the intensity dependent refractive index change of one of the media has been analyzed in detail. Bistable and multistable transmission and reflection characteristics are predicted.[1] Effects associated with the self-focusing of light have also been studied. In general, the basic problem is choosing a suitable nonlinear medium so that only relatively moderate power lasers are needed.

In some recent studies[5–8] nematic liquid crystals have been shown to exhibit large nonlinear optical effects. In this letter, we describe an experiment using a nematic liquid crystal-glass interface in which the change from a total internal reflection state to a transmission state is observed. The experimental setup is schematically shown in Fig. 1. The prism surfaces enclosing the nematic liquid crystal are treated with HTAB (hexadecyltrimethyl-ammonium bromide) to achieve homeotropic alignment, i.e. the director axis of the liquid crystal is perpendicular (along y axis) to the prism surface. The incident light is polarized in the z direction and

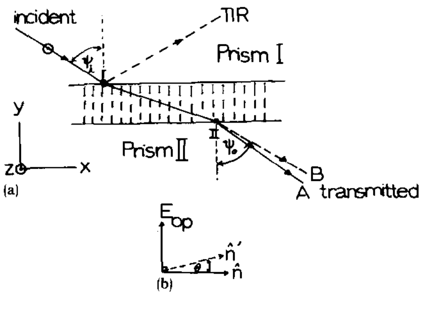

FIG. 1. Schematic of the TIR-transmission switching experiment. The nematic liquid crystal is sandwiched between the two prisms. Insert (b) shows the original orientation n and the tilted orientation n' of the director axis with respect to the optical field.