# Monolithic integration of GaAs light-emitting diodes and Si metal-oxide-semiconductor field-effect transistors

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A monolithic optoelectronic circuit, consisting of a GaAs light-emitting diode (LED) driven by a Si metal-oxide-semiconductor (MOS) transistor, has been fabricated. Light output as a function of applied gate voltage was measured. The LED's were fabricated in GaAs layers on Ge-coated Si substrates containing MOS transistors. Normal transistor performance was observed after the GaAs LED fabrication, indicating that GaAs and Si processing technologies appear to be compatible.

There exists a growing interest in utilizing GaAs optical devices for high-speed interchip and intrachip communications for Si based systems. Fabrication of a light-emitting diode (LED) and a laser on Ge-coated Si substrates has been reported.[1-3] It remains to be determined whether GaAs and Si processing technologies are mutually compatible, to enable the fabrication of GaAs optical devices on Si substrates already containing active electronic devices. To this end we report the first demonstration of a monolithic optoelectronic circuit combining GaAs and Si devices. Our circuit consisted of a GaAs LED driven by a Si metal-oxide-semiconductor field-effect transistor (MOSFET).

GaAs layers were grown using metalorganic chemical vapor deposition (MOCVD) at 650 °C in a low-pressure horizontal-reactor system. Since standard aluminum metallization used for Si devices cannot withstand this growth temperature, samples with refractory metal (Mo) contacts were used. To protect the Si transistors from the processing required for LED fabrication, the substrate was passivated with a layer of $SiO_2$. A 1 $mm^2$ area on the chip was exposed to the bare Si to provide a GaAs growth region.

Previously reported techniques were utilized to epitaxially deposit GaAs on the Si substrate by means of an interfacial layer of Ge.[1] A major concern of our study was whether the heat cycles necessary for the Ge and GaAs growths, 500 °C for ~30 min and 650 °C for ~40 min respectively, would modify the performance of the underlying Si devices. The gate length and width of the *n*-channel transistors are 1.2 and 1072 $\mu$, respectively. Figure 1(a) shows the initial current versus voltage (*I-V*) characteristic of one of the transistors. The offset in $V_D$ is due to poor contacts. Figure 1(b) shows the *I-V* characteristic following the LED fabrication. The GaAs growth cycle appears to have annealed out the initial problems with the ohmic contacts, resulting in more normal MOSFET *I-V* characteristics. A clearer indication of process induced changes in the MOSFET's would have been obtained if the original devices had not had ohmic contact problems. However, GaAs and Si processing technologies appear to be compatible in the sense that normal transistor action could be obtained from the Si MOSFET after the GaAs LED fabrication.

Surface emitting homojunction LED's were fabricated in a region of selective GaAs growth adjacent to the transistors as shown in Fig. 2. The *p-n* junction in the LED was formed by selectively doping with Zn and Se during the GaAs growth. The active area of the LED is $3.2\times10^4\ \mu^2$. Au:Ge:Ni and Ag/Mn/Ag alloyed ohmic contacts were made to the *n* and *p* layers. The alloying cycle consisted of heating to 345 °C for 1 min in a $H_2$ atmosphere. A mesa isolation etch to the Ge layer was performed to isolate each LED.

Emission from the LED's was observed using an infrared viewer and a Si photodiode. Photoluminescence measurements place the output peak at 868 nm. Light output versus current measurements demonstrated that the transistors were capable of driving the LED's. The circuit used is

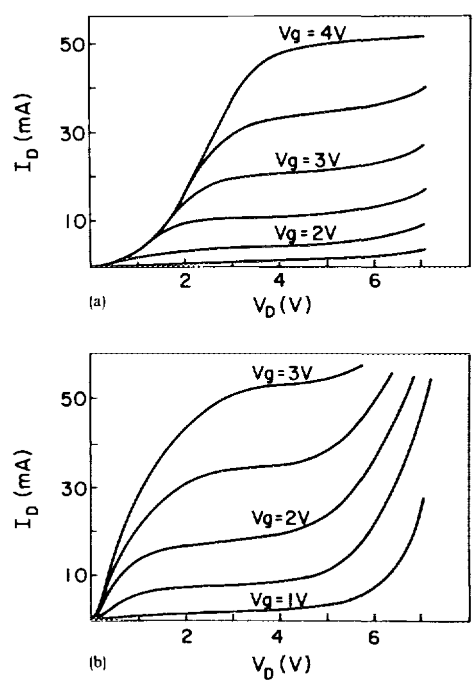


FIG. 1. *I-V* characteristic of an *n*-channel FET: (a) initial measurement and (b) post GaAs LED fabrication.

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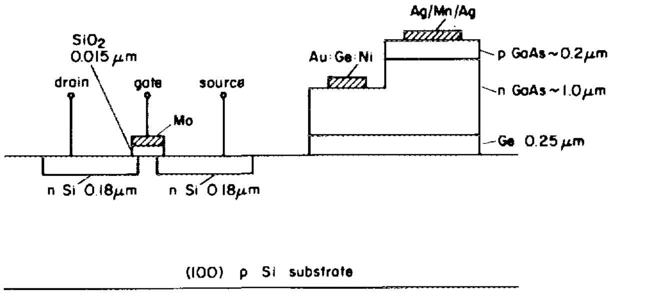


FIG. 2. Schematic illustration of the FET and LED structures on a single Si substrate.

shown in the upper inset of Fig. 3. Interconnection was accomplished by externally connecting the contact pads on the devices. $V_{DD}$, the voltage applied to the drain of the transistor, was pulsed using 10 $\mu$s pulses with a 0.1% duty cycle to avoid adverse heating effects. The measured power output for 9 V gate bias and $V_{DD} = 17$ V is shown in the upper oscilloscope trace in the lower inset to Fig. 3. The lower trace is $V_{DD}$ and the middle one the current pulse measured as a voltage across a 1 Ω series resistor. The 15 $\mu$s lag in the response of the circuit is due to the response time of the current amplifier used in the light detection circuit. The transfer function for the optoelectronic circuit, power output as a function of applied gate voltage, is plotted in Fig. 3 for various values of $V_{DD}$.

The LED's reported here are poor devices in that they suffer from two problems. First the Si surface where the GaAs growth was to occur was accidentally contaminated resulting in GaAs growth problems. Second the *p* layer was grown too thin which led to a propensity of the junction to short out during the alloying of the *p* contact. However, it is important to emphasize that these problems which account for the poor performance of the devices were *not* inherent to the processing required to produce the monolithic combination, and do not detract from this first demonstration of a GaAs/Si optoelectronic integration. Similar processes have yielded excellent MOS circuits, and LED's which were an order of magnitude more efficient.[4]

Questions remain to be answered before a GaAs/Si optoelectronic circuit can be incorporated into a high-speed interchip communication system. Our current response time measurements were bandwidth limited to 67 kHz by the detection circuitry. We expect the actual modulation rate to be significantly higher.

In summary, a GaAs light-emitting diode has been monolithically integrated with a Si MOS transistor, which demonstrates the compatibility of GaAs and Si technologies. A transistor was used to drive an LED and the transfer function for this monolithic optoelectronic circuit was obtained.

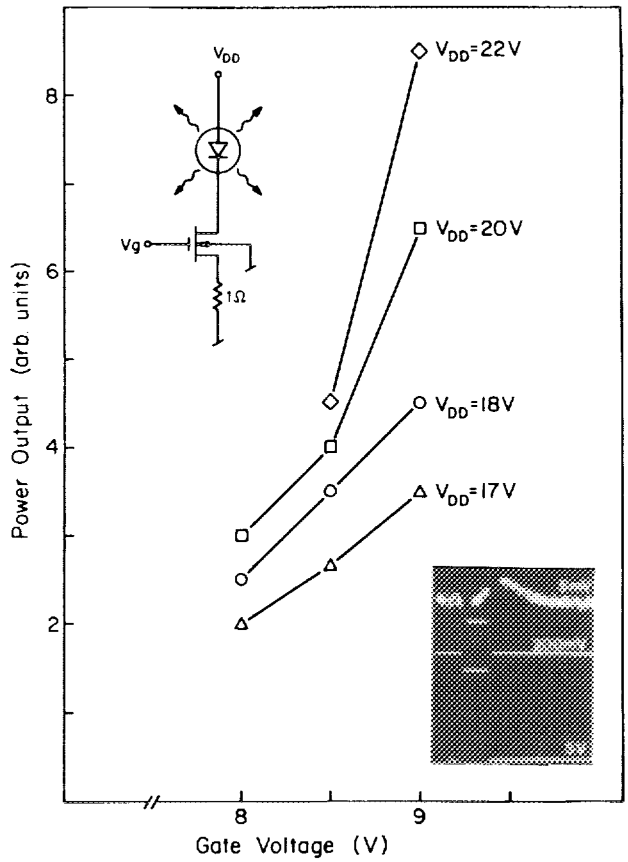


FIG. 3. Light output from the optoelectronic circuit as a function of applied gate voltage. The lower inset shows an oscilloscope trace of the output pulse corresponding to $V_g = 9$ V and $V_{DD} = 17$ V. The upper inset shows the circuit used.

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