Monolithic Integration of GaAs Devices with Completely Fabricated Si CMOS Circuits

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The performance of all-electronic analog-to-digital converters (ADCs) is limited by inadequate bandwidth and large aperture uncertainty. To surpass the current limits, we investigated a time-interleaved, integrated photoconductive-sampling-based photonic A/D conversion system, utilizing low-temperature GaAs (LT-GaAs) metal-semiconductor-metal (MSM) photoconductive switches as optical sampling gates [1, 2]. We previously flip-chip bonded ultrafast LT-GaAs switches with a CMOS ADC chip and demonstrated a high bandwidth, two-channel prototype ADC system [1].

In order to minimize circuit parasitics, monolithic integration is essential. The common approach for monolithic integration is to grow the GaAs device layers onto the Si CMOS wafer prior to final level metallization and then finish the metallization after the growth of the GaAs devices. However, this creates significant fabrication complications due to the mismatch between different equipment used to fabricate Si circuits and GaAs devices and potential cross-contamination issues. Since high-speed MSM devices utilize controllable material defects to shorten carrier lifetime, we have explored the possibility of directly growing GaAs films at low temperatures on top of <u>completely fabricated</u> Si chips to enable on-chip monolithic integration. The most critical issue is not to modify the characteristics of the underlying Si circuits by the GaAs film growth and processing steps.

We initially studied the LT-GaAs on Si growth [3, 4]. MSM switches made from LT-GaAs on Si showed ~2ps switching time and the responsivity was comparable to its counterpart on a GaAs substrate. However, modern ICs usually have more than six metal layers. In order to grow on Si, deep etching of a finished chip is needed to expose the Si surface. This creates deep trenches and causes metal step coverage problem. To solve this problem and simplify the processing, we studied direct growth of GaAs on SiO_2 or Si_3N_4 at relatively low temperatures. At around 400ºC, growing GaAs on amorphous dielectrics results in polycrystalline GaAs. The grain boundaries act as trapping and recombination centers, resulting in short carrier life time. Using 1 μm poly-GaAs grown on SiO_2 at 400ºC, we made MSM switches with 1μm finger width and 0.8μm finger spacing. A FWHM switching window of ~1.65ps was obtained with electro-optic sampling technique under the illumination of a 12.4pJ (100μW) Ti/sapphire mode-locked laser pulse with 1V bias voltage. Fourier transform indicates a ~270GHz 3dB bandwidth. The responsivity is 80mA/W under the above testing conditions.

A suitable high-speed Si chip was not available when we attempted to demonstrate the on-chip integration. For proof-of-concept purpose, we used a moderate speed (30MHz) optical receiver chip. As long as we achieve a functional integrated system without degrading the Si circuits, it would prove the validity of this approach. Fig. 1 is the circuit schematic of the receiver. It is a two-stage amplifier with a buffered input stage and a differential gain stage. The MSM switches are integrated at the input nodes. Fig. 2(a) is a picture of the finished CMOS receiver chip, passivated with SiO_2/Si_3N_4 dieletrics. The white squares are arrays of glass cut openings through which GaAs switches are to be connected to the underlying Si circuits. The integration process is very simple, which is exactly the beauty of this approach. 1μm poly-GaAs was grown on top of the cleaned chip at 400ºC by MBE. MSM switches were patterned on the poly-GaAs film using a standard lift-off process. GaAs grown inside the glass cuts was wet-etched to expose the metal layer below. Fig. 2(b) is a picture of the chip after integration. Four pairs of differential poly-GaAs switches were connected to the Si-circuitry through the glass cuts by a lift-off process.

Fig. 3 shows the DC characteristics of the optical receiver. With a constant continuous-wave laser power triggering the switch, the MSM bias voltage (V_{MSM}) was varied to indirectly change the input node voltage (V_{in}) of the receiver. The corresponding output voltage (V_{out}) was recorded to obtain the transfer function. Changing laser power, a different photocurrent and therefore another transfer function is generated. In this experiment, we indirectly measured the transfer function of the integrated receiver and demonstrated that after integration, we achieved a properly functioning optical receiver with typical input-output characteristics.

It is important that the integration process not to affect the Si circuit performance. We fed the amplifier with two differential electrical signals, and measured the output step response in order to compare the AC characteristics of the amplifier (without MSM switches) before and after the integration. Fig. 4 confirms that the step response is not changed. The rise times of the amplifier before and after integration are both ~ 11ns. The 0.2ns difference is within chip to chip variation. The amplifier gain is measured to be 3 for both chips. In addition, the circuit biasing points stay the same. It proves that our approach is safe for a finished Si CMOS chip with metallization.

In conclusion, we have monolithically integrated poly-GaAs switches with a <u>completely fabricated</u> CMOS amplifier and obtained a functional optical receiver without modifying the Si circuit performance. The beauty of this approach is its simplicity, minimum fabrication disturbance limited entirely to the tailend Si processing and greater

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applicability into much broader areas, such as optical interconnects. To our knowledge, this is the first time a fully monolithic on-chip integration has been successfully achieved.

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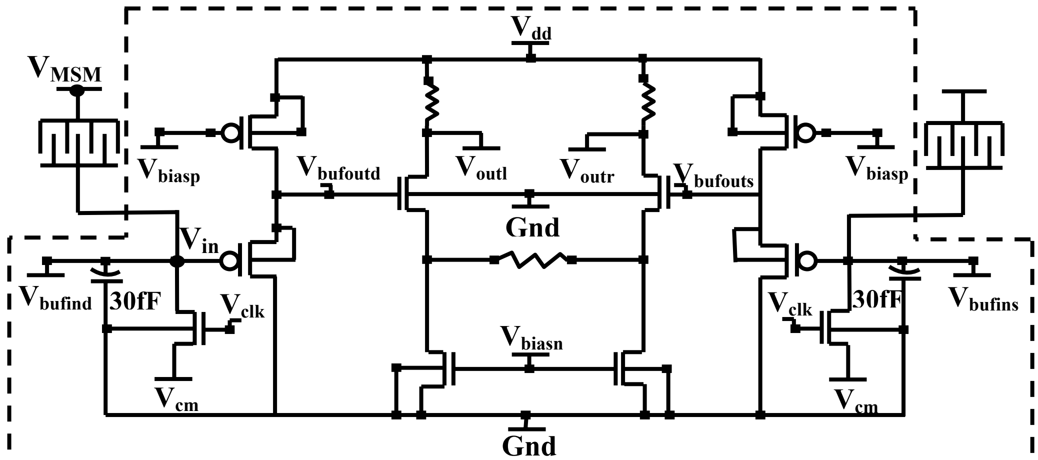

Fig. 1. Inside the dotted line is the circuit schematic of the receiver chip. The differential pair of the poly-GaAs MSM switches is integrated at the receiver input nodes.

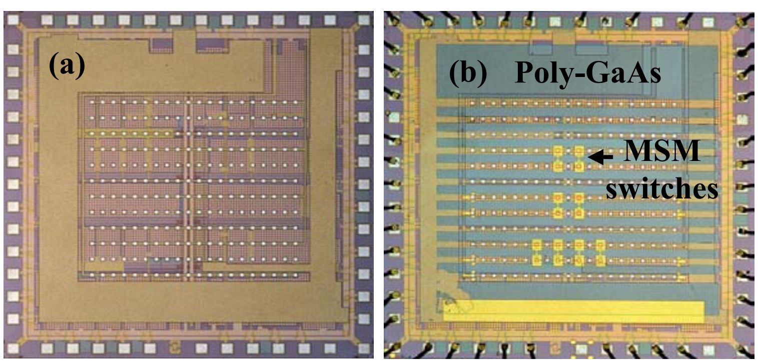

Fig. 2. (a) Picture of the completely fabricated CMOS receiver chip. (b) Picture of the chip after integration. Gray areas are poly-GaAs film.

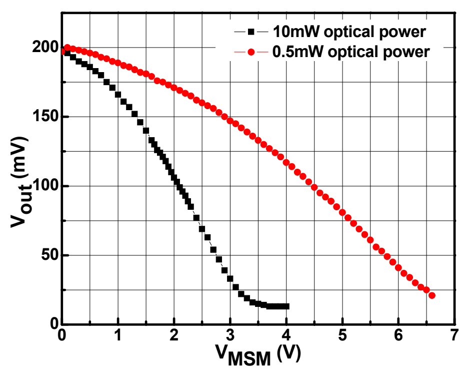

Fig. 3. Input-output characteristics of the integrated optical receiver with MSM switches. CW laser λ=850nm.

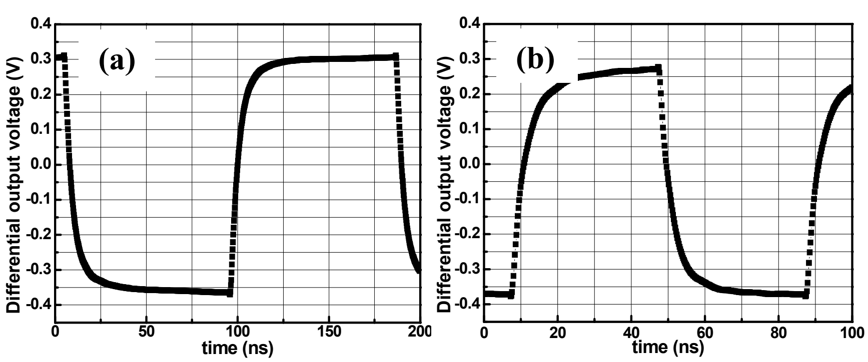

Fig. 4. Step response of the amplifier (a) before and (b) after integration. The 10% to 90% rise time in (a) is 11ns and in (b) is 11.2ns. The amplifier gain is 3. Circuit biasing conditions are: Vdd = 2.5V; Vclk = 0.66V; Vcm = 0V; Vbias,n = 0.79V; Vbias,p = 1.9V.