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A Long-Wavelength Optical Receiver Using a Short-Channel Si-MOSFET

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Recent improvements in fine-line technology have resulted in silicon metal oxide semiconductor field-effect transistors (MOSFETs) with channel lengths between 0.2 and 0.8 μm. We have measured the low-frequency noise in these transistors and find it to be smaller than that in comparable GaAs-metal Schottky valve field-effect transistors (MESFETs). Theoretical considerations on the FET noise and experimental results at 45 Mb/s indicate that Si-MOSFETs can compete with GaAs-MESFETs in hybrid photoamplifier circuits. As a natural extension, Si-MOSFETs can also be used for the complete monolithic integration of the receiver circuit with the benefits of reliability and improved performance.

I. INTRODUCTION

In the absence of high-performance avalanche photodiodes for long-wavelength optical receivers, p-i-n photodiodes with low-noise amplifiers have been used.[1] The amplifiers are designed with ultra-low-noise components to realize high receiver sensitivities. Up until now, GaAs-metal Schottky valve field-effect transistors (MESFETs) were used exclusively as low-noise components at bit rates less than 300 Mb/s.[2,3] We have fabricated a short-channel Si-metal oxide semiconductor field-effect transistor (MOSFET)[4] and used this MOSFET in a hybrid integrated receiver circuit at 45 Mb/s. The receiver's performance is similar to that of a receiver employing a GaAs-MESFET. The use of

Si-MOSFETs creates the opportunity for monolithic integration of the entire front-end amplifier, with the ensuing benefits of circuit reliability and stability.

In the past, Si-FETS were ignored for this application because they were believed to have a lower transconductance than GaAs-FETs of comparable dimensions. This was due to the difference in mobility between the two materials. Recent improvements in fine-line technology have resulted in silicon MOSFETs with short channels from 0.2 to 0.8 μm. Also, we find that a short-channel Si-FET operating in the saturation region of the electron drift velocity has a transconductance comparable to that of the best GaAs-FET.[5,6] GaAs-FETS exhibit additional noise because of electron scattering in the high electric field of the channel. Since this effect is generally absent in Si-FETs,[7,8] the receiver sensitivity obtained using a Si-MOSFET is now expected to be comparable to or slightly better than that obtained using a GaAs-MESFET.

II. SILICON SHORT-GATE MOSFET

Table I lists the characteristics of a Si-NMOSFET with a channel length between 0.5 and 0.8 μm, and for comparison shows the typical characteristics of a GaAs-MESFET with a channel length between 0.5 and 1.0 μm. The figure of merit, g_m/C of a Si-N-channel metal oxide semiconductor field-effect transistor (NMOSFET) is smaller than that of a GaAs-MESFET when structures with the same dimensions are compared.[6] However, the noise factor, Γ, of a Si-NMOSFET is smaller than that of the GaAs FET if induced gate noise and its correlation with channel noise are considered.[5,7-9] The mean square of the equivalent input noise current of an FET is given by

$$i_n^2 = 4k\Gamma \frac{\omega^2 (C_{gs} + C_{in})^2}{g_m} \Delta f$$

$$\Gamma = P + \left| \frac{C_{gs}}{C_{in} + C_{gs}} \right|^2 R - 2Q \left| \frac{C_{gs}}{C_{in} + C_{gs}} \right|,$$

where Γ is the noise factor, g_m the transconductance, C_{gs} the gate-source capacitance, and C_{in} the input capacitance consisting of the

Table I—Typical Si-NMOSFET characteristics

	Gate-Source Capacitance (pF)	Transconductance (mS)	Figure of Merit, g_m/C_{gs} (mS/pF)
Si-NMOS	0.5 to 0.8	40 to 50	60 to 70
GaAs-MESFET (0.5 to 1.0 μm)	0.2 to 0.5	25 to 50	60 to 140

Table II—Noise factor Γ, *P*, *Q*, *R* for Si-NMOSFET

P	0.763
Q	−0.206
R	0.245
Typical Γ $C_{gs} = 0.5_{pF} C_{in} = 0.5_{pF}$	1.03

photodiode capacitance and any parasitic capacitance. P is the noise factor for the channel noise, R is the noise factor for the induced gate noise, and Q is the correlation factor. Table II indicates the values of Γ, P, Q, and R for a Si-FET with a 0.5-μm channel length. The noise factor, Γ, for the Si-FET (1.03) is much smaller than the value for a typical GaAs-FET (1.78).

Low-frequency $1/f$ noise in FETs has an important effect on the performance of an optical receiver at low bit rates. We have measured the low-frequency noise of both a Si-NMOSFET and a GaAs FET. The results are shown in Fig. 1. Whereas the low-frequency noise for the GaAs FET does indeed have a $1/f$ dependence, the results show a $f^{-1/2}$ dependence for the Si-NMOSFET. This result has not yet been explained.

The noise measured in Fig. 1 was normalized to the expected channel noise $4kT\Gamma\Delta f/g_m$. The FET transconductance, g_m, was 48 mS; the filter bandwidth, Δf, was 3.1 kHz; and the noise factor, Γ, was 1.03 for

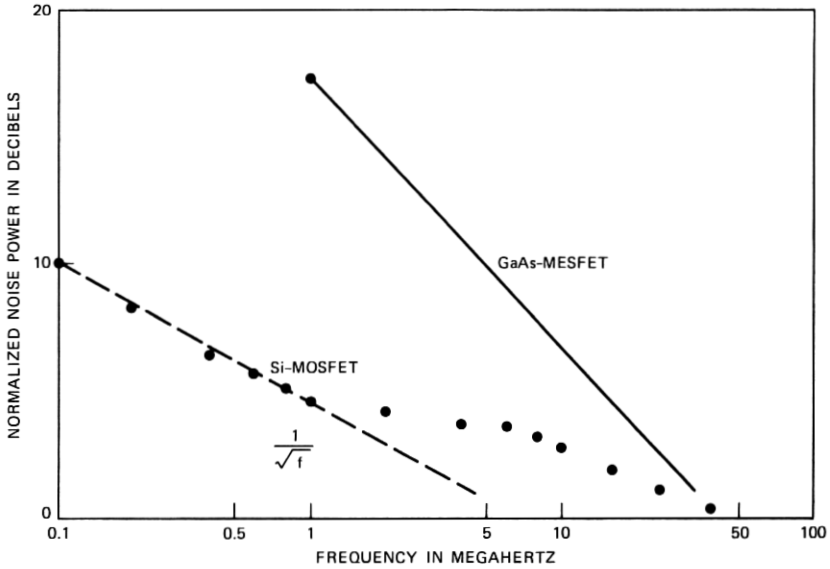

Fig. 1—Low-frequency characteristics of Si-NMOSFET. The dotted points show results measured with a 3.1-kHz filter. The best fit showed by the dashed line has a $f^{-1/2}$ slope. The $1/f$ noise of the GaAs-MESFET is shown (solid line) for comparison.

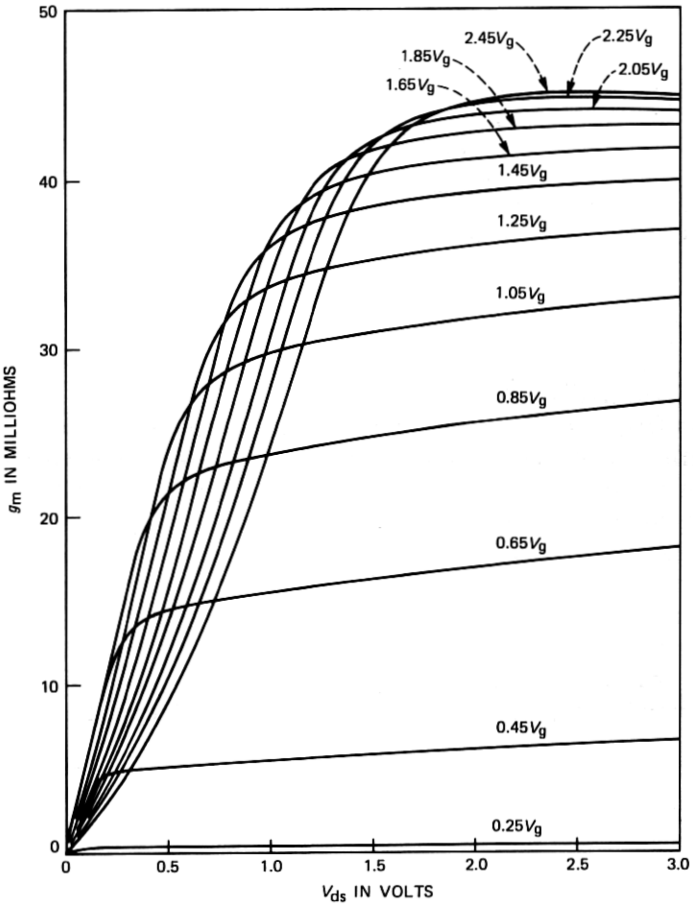

Fig. 2—Transconductance of Si-NMOSFET. Parameters are the gate-source voltage.

the Si-NMOSFET and 1.78 for the GaAs FET. In the Si-NMOSFET, the channel noise exceeded the $4kT\Gamma\Delta f/g_m$ value. The excess noise is believed to be thermal noise associated with the large series resistance of the polysilicon gate. This series gate resistance can be reduced by improved fabrication techniques, such as metallizing the gate. From Fig. 1, the noise corner frequency, f_c, for the Si-NMOSFET is $\approx$5 MHz. The noise corner frequency for the GaAs FET is $\approx$30 MHz. Therefore, even with the excess noise from the gate resistance, the low-frequency noise contribution of the Si-NMOSFET is clearly smaller than that of the GaAs FET.

Another FET parameter that affects its performance in an optical receiver is gate leakage current. The gate leakage current contributes shot noise at the receiver front end. Again, the Si-NMOSFET is

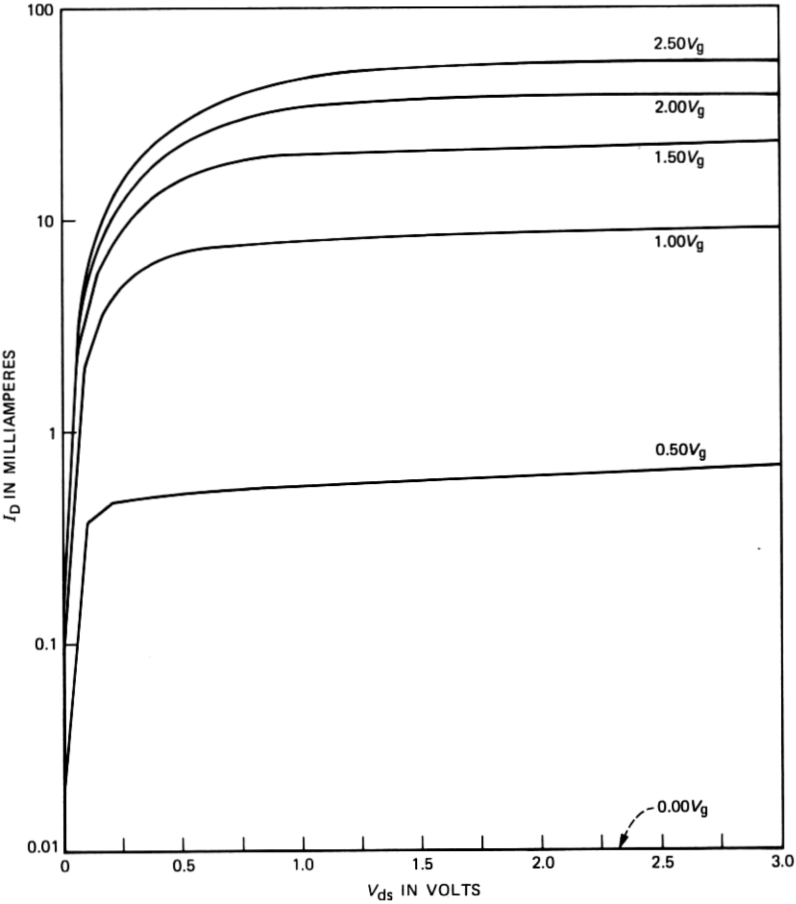

Fig. 3—I-V characteristics of Si-NMOSFET. The parameters are the gate-source voltage.

superior to the GaAs FET. The measured gate leakage current of the GaAs FET is ≈5 nA. The measured gate leakage current of the Si-NMOSFET is ≈10 pA.

Based on these measurements, we have calculated the sensitivity of a 45-Mb/s optical receiver using both a Si-NMOSFET and a GaAs FET. The receiver sensitivity is given by

$$\eta \bar{P} = \left| \frac{h\nu Q}{q} \right| \langle i^2 \rangle_T^{1/2},$$

where the prefactor $(h\nu Q/q)$ is 4.950 W/A at 1.3 μm and at 10^{-7} bit error rate; and where the equivalent input noise current, $\langle i^2 \rangle_T$, is given by

$\langle i^2 \rangle_T = 2qI_{\mathrm{L}}I_2B$	Shot noise from the gate leakage current, I_{L}.
$+\ 2qI_{\mathrm{D}}I_2B$	Shot noise from the photodiode dark current, I_{D}.
$+\ \dfrac{4kT}{R_F}I_2B$	Thermal noise from the bias resistor, R_F.
$+\ \dfrac{16\pi^2kT\Gamma(C_{\mathrm{T}}^2)I_3B^3}{g_{\mathrm{m}}}$	Channel noise in the FET.
$+\ \dfrac{16\pi^2kT\Gamma(C_{\mathrm{T}})^2f_cI_fB^2}{g_{\mathrm{m}}}$	$1/f$ noise in the FET.
$+\ \langle i^2 \rangle_c$	Postamplifier noise,

where B is the bit rate, and I_2, I_3, etc. are Personick integrals associated with the circuit noise. Assuming R_F to be 500 kΩ, and the p-i-n photodiode dark current, I_{D}, at 30 nA, the sensitivity of a 45 Mb/s receiver at 10^{-7} bit error rate is −51.3 dBm for a GaAs FET front-end amplifier and −51.8 dBm for a Si-NMOSFET front-end amplifier.

III. EXPERIMENTS

The Si-NMOSFET used for our experiments was fabricated on a *p*-type substrate (carrier concentration $\approx 2 \times 10^{15}/\mathrm{cm}^3$) with an implanted

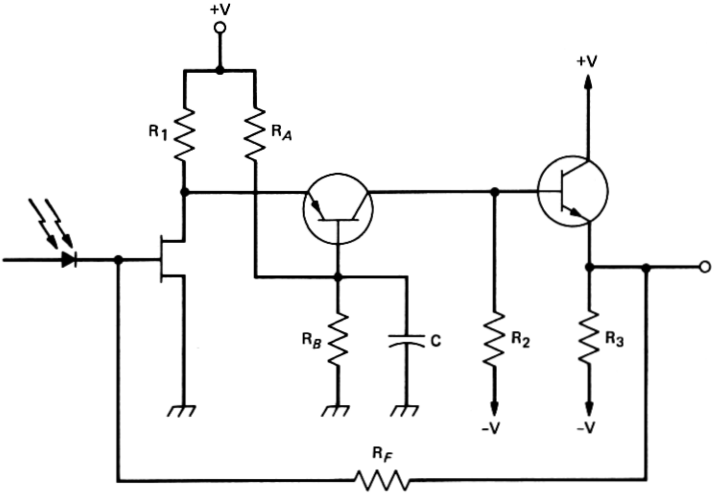

Fig. 4—Front-end amplifier circuit diagram with three active components involved. The first stage with the Si-NMOSFET provides a high input impedance. The second stage p-n-p transistor cascode circuit provides a gain stage and reduces the Miller effect. The last stage is an emitter follower for low output impedance.

n-layer (carrier concentration ≈$5 \times 10^{16}/cm^3$), which had a thickness between 0.5 and 0.6 μm.[4] The channel width was 500 μm, and the effective channel length was 0.45 μm.[5] The gate-source capacitance was 0.5 pF and the transconductance was 45 mS. The gate leakage current was ≈10 pA. Figures 2 and 3 show the drain current and transconductance of the Si-NMOSFET versus drain source voltage with different gate voltages.

We have fabricated a transimpedance front-end circuit[3] using an InGaAs p-i-n photodiode with the Si-NMOSFET as the first amplifier stage. The circuit is shown in Fig. 4. The primary gain was achieved in the second stage, which used a p-n-p transistor. The third stage was an emitter-follower circuit using an n-p-n transistor. The feedback

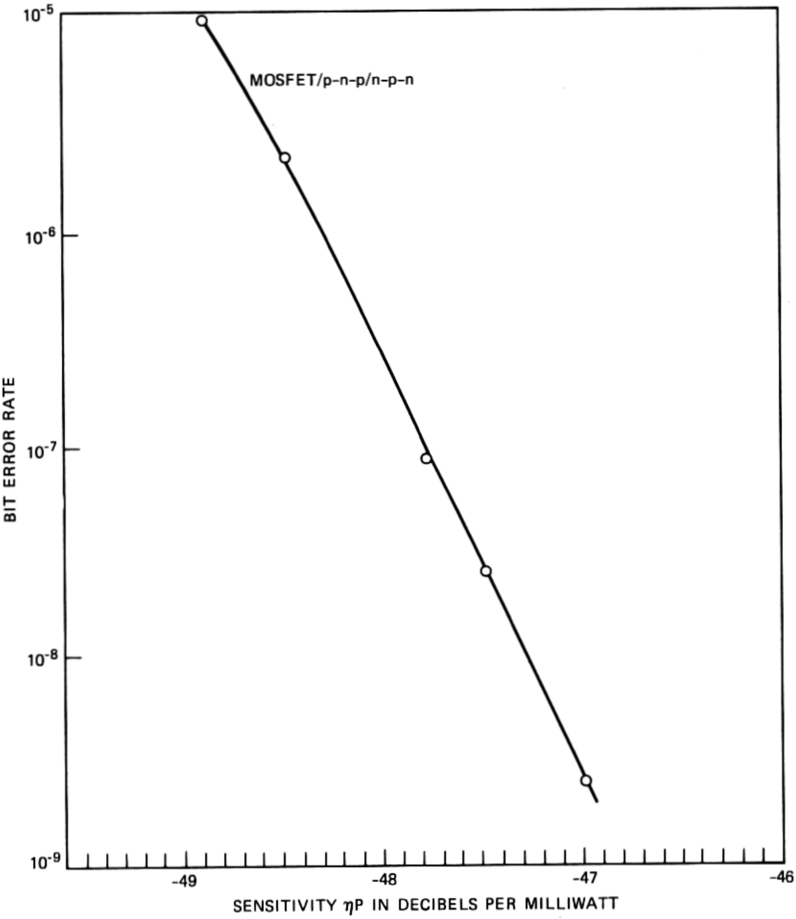

Fig. 5—Error-rate measurement of an InGaAs p-i-n-Si-NMOSFET receiver at 45 Mb/s.

circuit was 500 kΩ. The bit error rate was measured using a 44.7 Mb/s pseudorandom nonreturn to zero (NRZ) optical signal from an InGaAsP LED emitting at 1.3 μm. The receiver circuit was combined with a regenerator circuit and a retiming circuit designed for optical receivers. As shown in Fig. 5, the measured sensitivity at 10^{-7} bit error rate was −47.8 dBm (−51.8 dBm theoretical). With a GaAs FET first-amplifier stage, the same receiver circuit had a measured sensitivity of −49.5 dBm (−51.3 dBm theoretical).

IV. CONCLUSION

Further work is in progress to improve the Si-NMOSFET receiver performance and to integrate the front-end amplifier. The circuit, especially the second stage, is not presently optimized. Also, the Si-NMOSFET has a high series gate resistance because the gate was fabricated with polysilicon. The noise penalty associated with this resistance can be eliminated by metallizing the gate.

In conclusion, theoretical considerations and our first experiments indicate that Si-NMOSFETs can have sensitivity performance comparable to that of GaAs FETs in a 45-Mb/s optical receiver. The natural extension of this result is the complete monolithic integration of the entire receiver circuit using silicon fine-line MOS technology.

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