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Analysis of Optically Controlled Microwave/Millimeter Wave Device Structures

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Rainee N. Simons and Kul B. Bhasin
Lewis Research Center
Cleveland, Ohio

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ANALYSIS OF OPTICALLY CONTROLLED MICROWAVE/MILLIMETER WAVE DEVICE STRUCTURES

Rainee N. Simons* and Kul B. Bhasin
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

SUMMARY

The light-induced voltage and the change in the source-to-drain channel current under optical illumination higher than the semiconductor bandgap for GaAs MESFET, InP MESFET, $Al_{0.3}Ga_{0.7}As/GaAs$ high electron mobility transistor (HEMT) and GaAs permeable base transistor (PBT) were analytically obtained. The GaAs PBT and GaAs MESFET have much higher sensitivity than InP MESFET. The $Al_{0.3}Ga_{0.7}As/GaAs$ HEMT is observed to have the highest sensitivity. Variation in device parasitics due to optical illumination and its effect on the cutoff frequencies f_T and f_{max} are also investigated.

INTRODUCTION

Direct optical control of microwave devices in GaAs monolithic microwave integrated circuits (MMIC's) can result in better switching, amplitude and phase control in amplifiers, and frequency control in oscillators (ref. 1). Furthermore, it allows use of optical fiber technology for the interconnecting MMIC's, thereby reducing cross talk and electromagnetic interference. It also enhances efficiency and speed of operation (ref. 2).

Several authors have experimentally investigated the effect of light on the dc characteristics of GaAs metal semiconductor field effect transistor (MESFET) (refs. 3 and 4) and its effect on the S-parameters (ref. 5). The optical absorption coefficient and energy bandgap of III-V compound semiconductors can be tailored to a particular wavelength by adjusting the mole fraction (x) of its constituents (ref. 6). Besides, the III-V compound semiconductor devices can be integrated with other MMIC components on a single semi-insulating GaAs or InP substrate (ref. 7). These offer further advantages for direct optical control of microwave devices.

We investigated the effect of light on several III-V compound semiconductor devices, such as, GaAs MESFET, InP MESFET, $Al_xGa_{1-x}As/GaAs$ high electron mobility transistor (HEMT), and GaAs Permeable Base Transistor (PBT). The computed results illustrate (a) the light-induced voltage as a function of the incident optical power density, (b) the change in the drain current, with change in optical power density, as a function of the drain to source voltage, and (c) the variation in the device parasitics due to optical illumination and its effect on the cutoff frequencies f_T and f_{max}.

LIGHT INDUCED VOLTAGE

The operation of these microwave devices as photodetectors and amplifiers depend on the photogeneration of electron-hole pairs in their active layer.

*NRC-NASA Research Associate.

Figure 1 illustrates several techniques for the direct optical control of microwave solid-state devices. In these techniques light from a laser or a light-emitting diode (LED) (ref. 14) or an optical waveguide (ref. 15) is made to strike the active layer of the device. The incident optical power increases the concentration of the minority carriers, for example, the holes in an n-type channel. This increase in hole concentration Δp is proportional to the incident optical power P_{opt}, the wavelength of the incident light λ, the optical absorption coefficient of the semiconductor α, the thickness of the active layer d, and the minority carrier life time τ. Expressed mathematically, Δp is (refs. 8 and 9)

$$\Delta p = \frac{\tau}{d}\left[\frac{P_{opt}\lambda}{hc}\right]\left(1 - e^{-\alpha d}\right) \tag{1}$$

where h is Planck's constant (6.62617×10^{-34} J sec) and c is the speed of light in vacuum (2.99792×10^{8} m/sec). The quantity inside the square brackets represents the number of photons of wavelength λ falling on unit area per second.

The light-induced voltage V_{lit} is expressed as (refs. 8 and 9)

$$V_{lit} = \frac{KT}{q}\ln\left(\frac{p + \Delta p}{p}\right) \tag{2}$$

where K is Boltzmann's constant (1.38066×10^{-23} J/K), T is the absolute temperature, q is the electronic charge (1.60218×10^{-19} C), and p is the equilibrium minority carrier concentration in the active layer (e.g., holes in an n-type channel) and is given by (ref. 8)

$$p = \frac{n_i^2}{n} \tag{3}$$

where n_i is the intrinsic carrier concentration ($1.79\times10^{6}/cm^{3}$) and n is the carrier concentration.

EFFECT OF LIGHT ON DRAIN CHARACTERISTICS

The drain current I_d as a function of the applied gate bias voltage V_{gs} and the drain to source voltage V_{ds} for a MESFET is expressed as (refs. 8 and 9)

$$I_d = \frac{q\mu n w d}{\ell}\left\{V_{ds} - \frac{2}{3}\frac{1}{V_p^{1/2}}\left[\left(V_{ds} + V_b - V_{gs}\right)^{3/2} - \left(V_b - V_{gs}\right)^{3/2}\right]\right\} \tag{4}$$

where μ is the electron mobility (5300 cm^2 V sec), W and ℓ are the gate width and length, respectively, V_b is the built-in Schottky barrier voltage, and V_p is the pinch-off voltage required to completely deplete the active layer, such that

$$V_p = \frac{qnd^2}{2\epsilon_0\epsilon_r} \tag{5}$$

In equation (5) ϵ_0 is the permittivity in vacuum (8.85418×10^{-12} F/mt), and ϵ_r is the relative permittivity of the active layer. Illuminating the MESFET is equivalent to forward biasing the gate of the MESFET by a voltage source equal to V_{lit}. The net voltage at the gate is therefore a superposition of the gate bias V_{gs} and V_{lit}.

The drain current I_{ds} for a depletion-mode (normally ON) HEMT is expressed as (ref. 10)

$$I_d = (37.8V_{gs} - 158V_{gs}^2 - 360V_{gs}^3 + 18.5) \quad \tan^{-1}\left(\frac{V_{ds}}{0.07 + 0.1\ V_{gs}} + 0.25\ V_{ds}\right) \tag{6}$$

For an enhancement-mode (normally off) HEMT, it is expressed as (ref. 10)

$$I_d = (49.8V_{gs} - 13.64)\ \tan^{-1}\left(\frac{V_{ds}}{0.143\ V_{gs}} + 0.5V_{ds}\right) \tag{7}$$

The net voltage at the gate is a superposition of V_{gs} and V_{lit}.

COMPUTED RESULTS

The thickness of the active layer, the gate width and length, and the doping density are presented in figure 2 for GaAs MESFET, InP MESFET, $Al_{0.3}Ga_{0.7}As$/GaAs HEMT, and GaAs PBT. The properties of the semiconductors used in the fabrication of these microwave devices is presented in table I. The computed light-induced voltage using equation (2) is presented in figure 3 as a function of the incident optical power density for the devices shown in figure 2. The light-induced voltage increases linearly with the incident optical power. Besides, at a fixed incident optical power density the $Al_{0.3}Ga_{0.7}As$/GaAs HEMT had the highest sensitivity, and the InP MESFET the lowest sensitivity. The sensitivity of GaAs PBT and GaAs MESFET were almost identical and fall midway between those of HEMT and InP MESFET.

The drain current for a GaAs MESFET computed using equation (4) is illustrated in figure 4 for several optical power density and gate-to-source dc bias. In these computations the gate metallization was assumed to be gold, which is perfectly transparent to light. In practice, however, this is not true. This limitation can be overcome if the gate metallization is indium tin oxide. Indium tin oxide (ITO) is transparent to visible light (ref. 11) and forms a good Schottky contact with GaAs (ref. 12). The computed drain characteristics for a GaAs MESFET with an indium tin oxide gate is shown in figure 5. *In figure 6 the ratio of the saturation drain current with and without illumi*nation as a function of the gate-to-source voltage at a fixed incident optical power density for a GaAs MESFET is shown. This figure shows that the optical gain of a normally off FET is maximum if the gate-to-source bias is such that the FET is in pinch-off condition.

The drain current characteristics for a InP MESFET with a Au/(n) InP Schottky gate computed using equation (4) is shown in figure 7.

The drain current characteristics for depletion- and enhancement-mode $Al_{0.3}Ga_{0.7}As/GaAs$ HEMT's computed using equations (6) and (7) are shown in figures 8 and 9, respectively.

The change in the gate to source capacitance C_{gs}, with and without illumination, as a function of the gate-to-source bias for a GaAs MESFET (HFET-1000-01) is presented in reference 13. There, C_{gs} is observed to increase with illumination by as much as 30 percent. The increase in C_{gs} tends to lower the unity current gain frequency f_T and the unity maximum available gain frequency f_{max}. However, this change in C_{gs} is exploited in optically tuning FET oscillators.

CONCLUSIONS

Light-induced voltages as a function of the incident optical power density for GaAs MESFET, InP MESFET, $Al_{0.3}Ga_{0.7}As/GaAs$ HEMT and GaAs PBT were obtained. The drain current characteristics for these devices for various incident optical power ensities were also obtained. The effect of light on the parasitics was qualitatively estimated.

The GaAs MESFET and PBT have much higher sensitivity to light than InP MESFET. However, the $Al_{0.3}Ga_{0.7}As/GaAs$ HEMT has the highest sensitivity. The change in the drain current with illumination was significant. The increase in C_{gs} with illumination tended to lower f_T and f_{max}.

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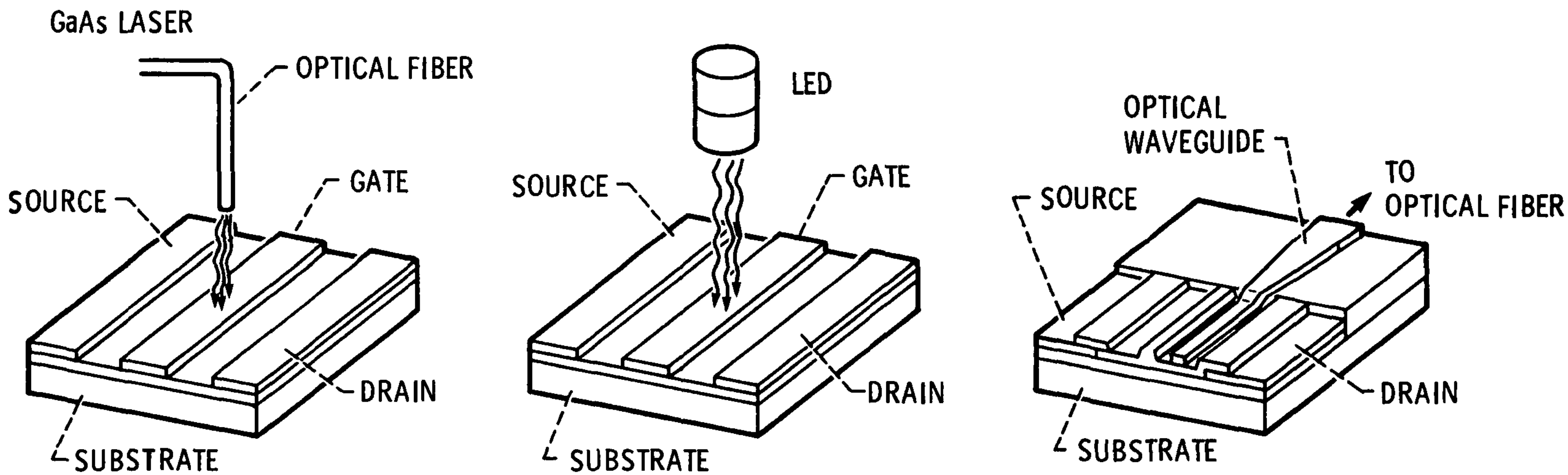
TABLE I - PROPERTIES OF SEMICONDUCTORS USED IN THE FABRICATION OF MICROWAVE DEVICES AT 300 K

Material	Electron mobility μ, cm^2/V sec	Intrinsic carrier concentration n_i, cm^{-3}	Optical absorption coefficient α, cm^{-1}	Wave length λ, μm	Minority carrier lifetime τ, sec	Relative permittivity, ϵ_r	Schottky barrier voltage, V_b
GaAs	5300	$1\ 78 \times 10^6$	$1\ 00 \times 10^4$	0 87	1×10^{-8}	13 1	Gold 0 9 ITO 0 95
InP	3300	$1\ 97 \times 10^9$	$1\ 80 \times 10^4$	1 06	1×10^{-8}	12 55	Gold 0 5
$Al_{0\ 3}Ga_{0\ 7}As$	9000	$2\ 5 \times 10^3$	$1\ 25 \times 10^4$	0 653	2×10^{-8}	12 2	Gold 1 11



(a) Optical fiber illuminating a MESFET. (b) LED illuminating a MESFET. (c) Optical waveguide coupling light to a MESFET.

Fig. 1. - Proposed techniques for direct optical control of microwave devices.

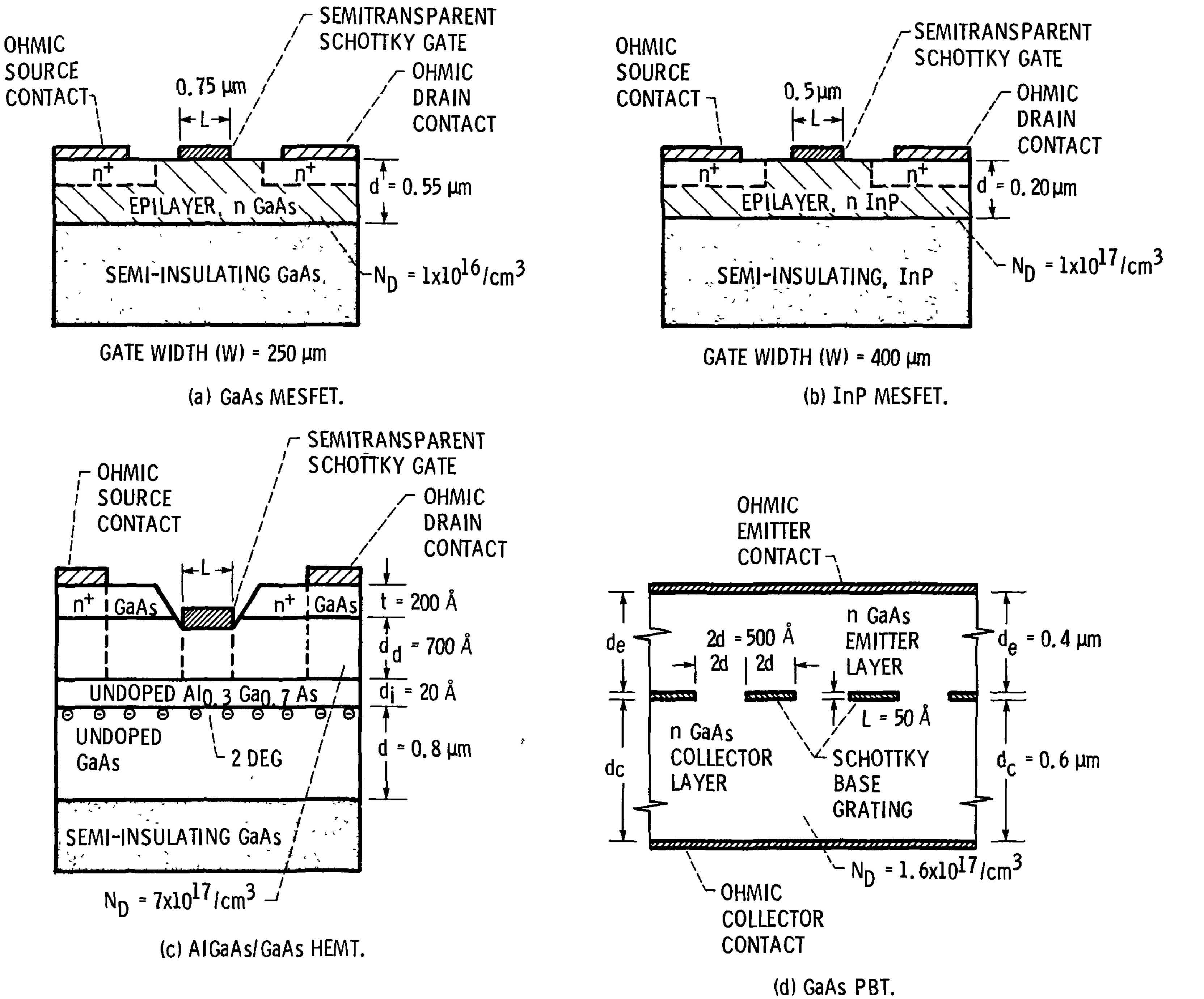


Fig. 2. - Material parameters of microwave device structures for direct optical control of monolithic microwave and millimeter-wave integrated circuits.

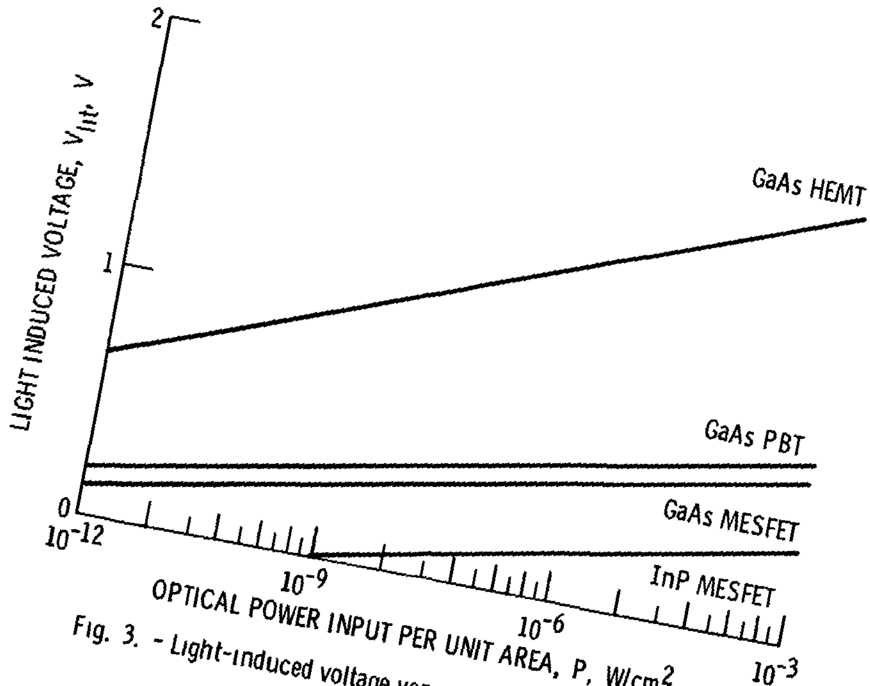


Fig. 3. - Light-induced voltage versus the incident optical power.

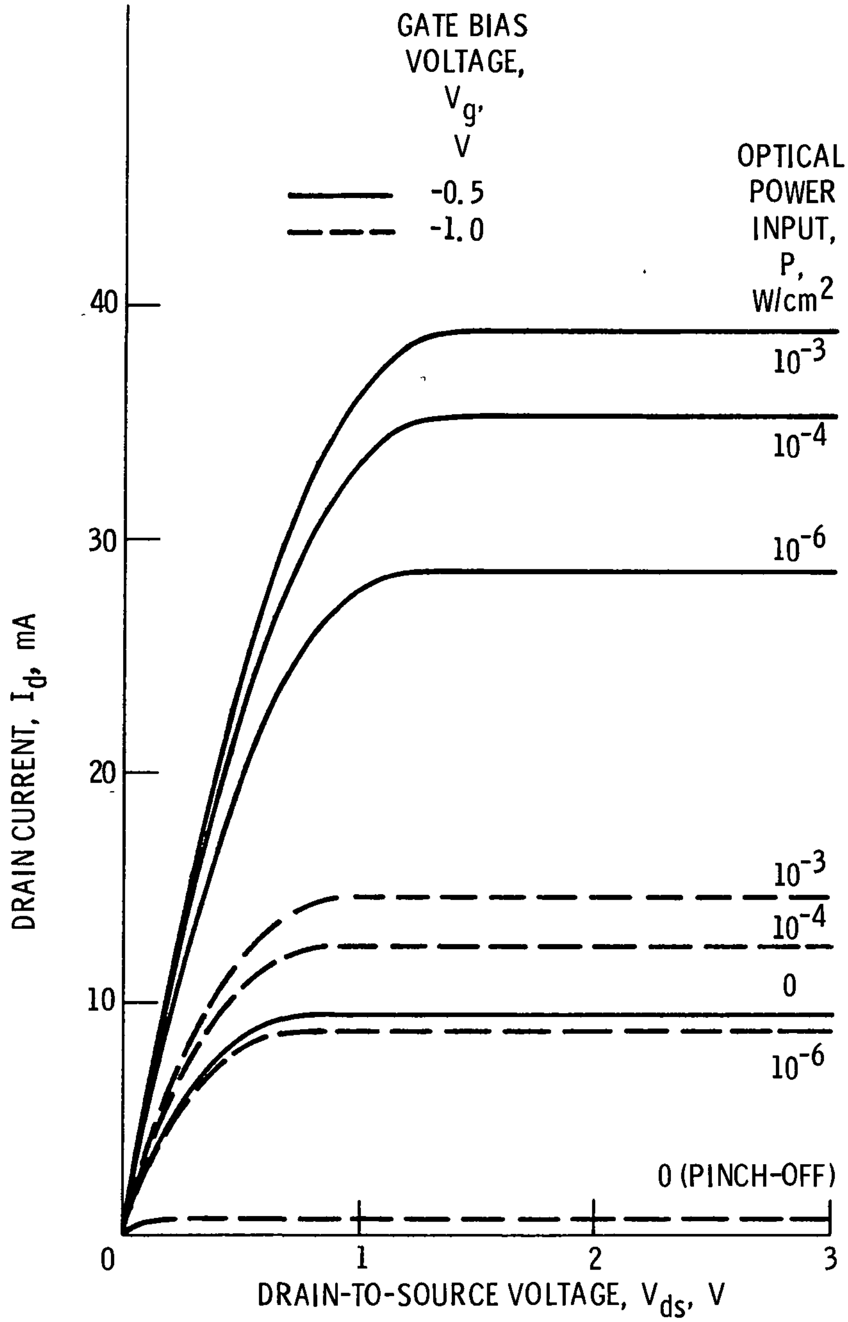


Fig. 4. - Drain current versus the drain-to-source voltage for GaAs MESFET with Au/(n) GaAs Schottky gate. Illumination wavelength, 0.87 μm.

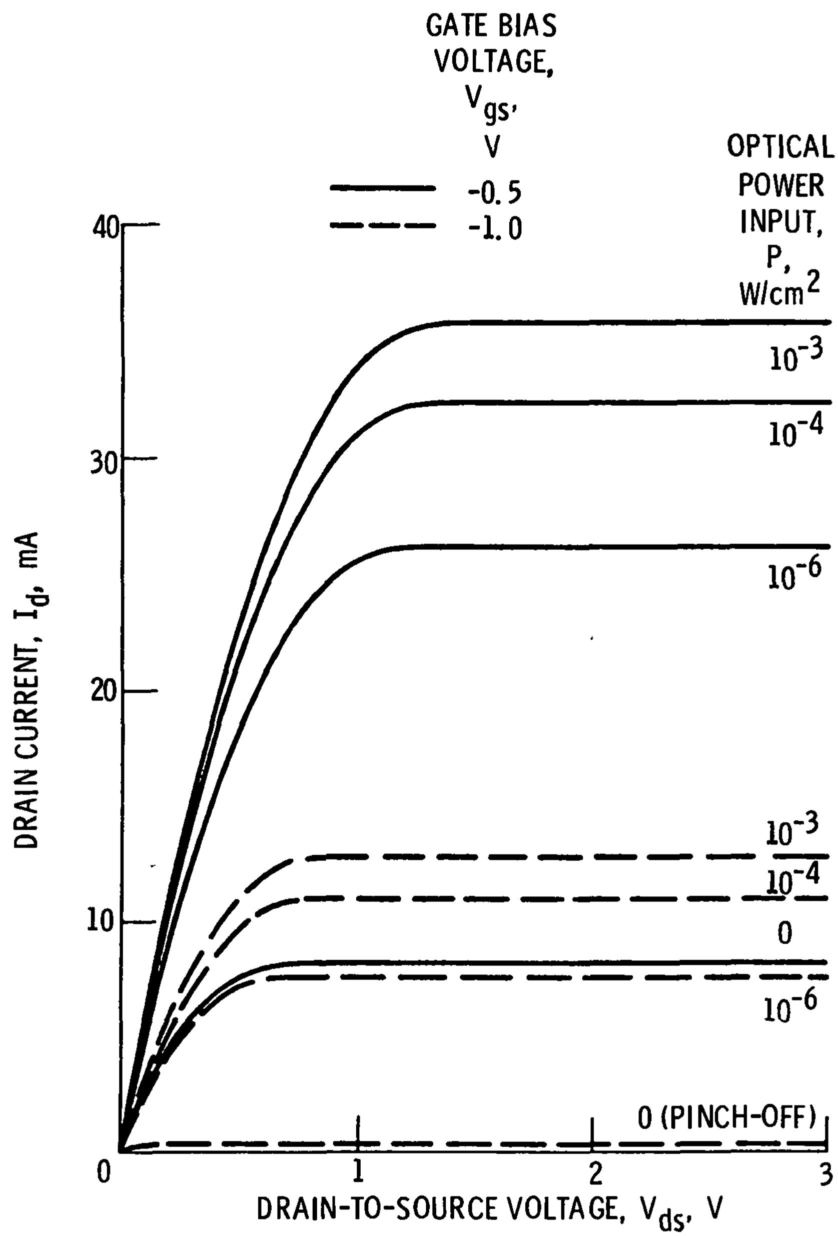


Fig. 5. - Drain current versus the drain-to-source voltage for GaAs MESFET with ITO/(n) GaAs Schottky gate. Illumination wavelength, 0.87 µm.

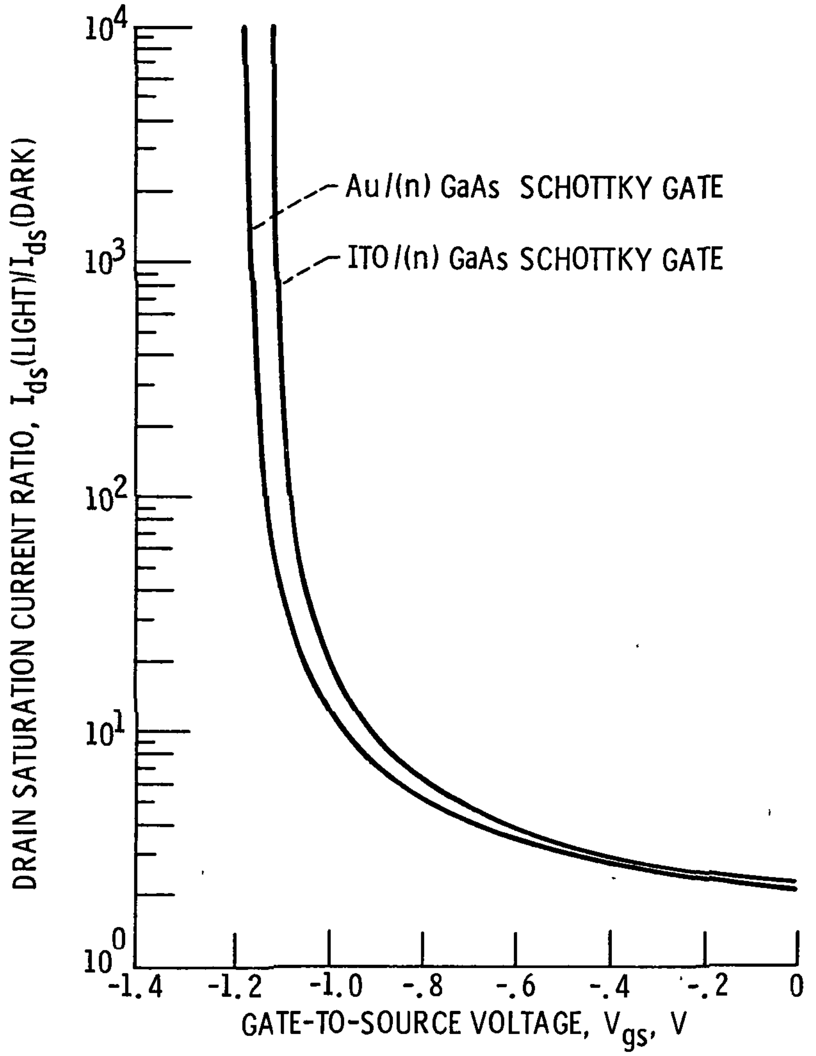


Fig. 6. - Ratio of drain saturation current with and without illumination versus the gate voltage for a GaAs MESFET with different Schottky gate configurations. The incident optical power level is kept constant.

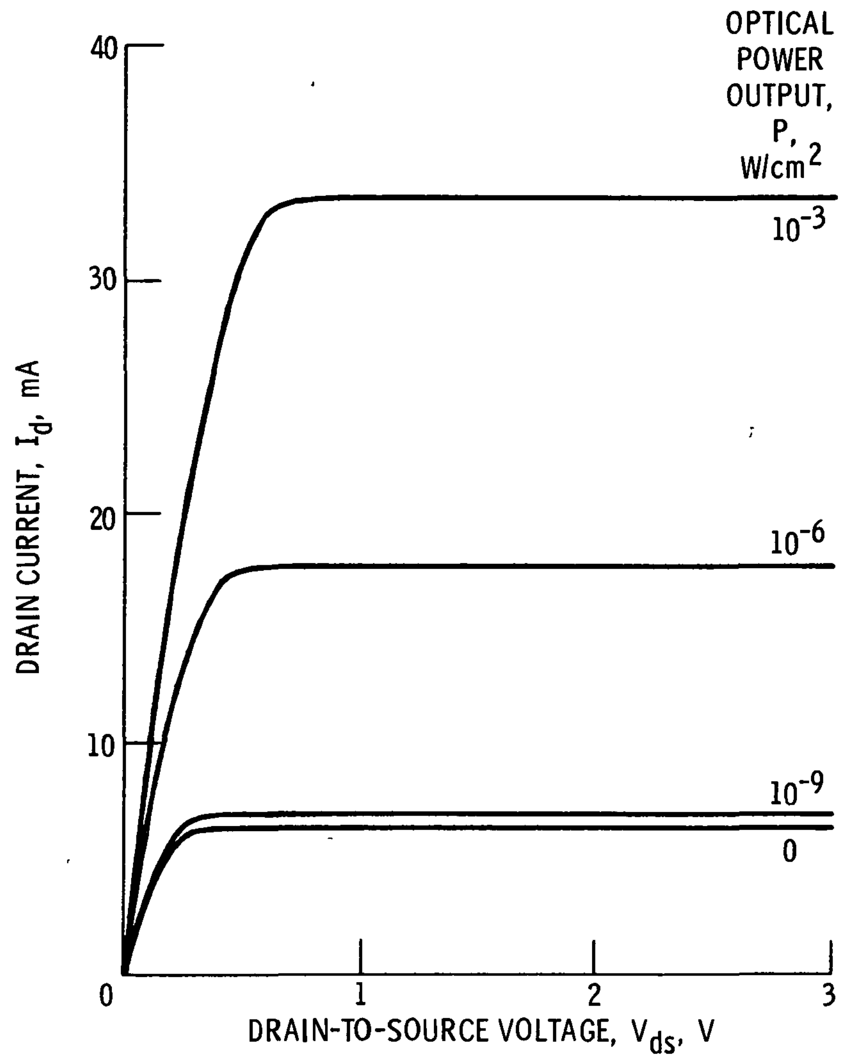


Fig. 7. - Drain current versus the drain-to-source voltage for InP MESFET with Au/(n) InP Schottky gate. Illumination wavelength, 1.06 μm; gate bias voltage, V_{gs}, -2.1 V.

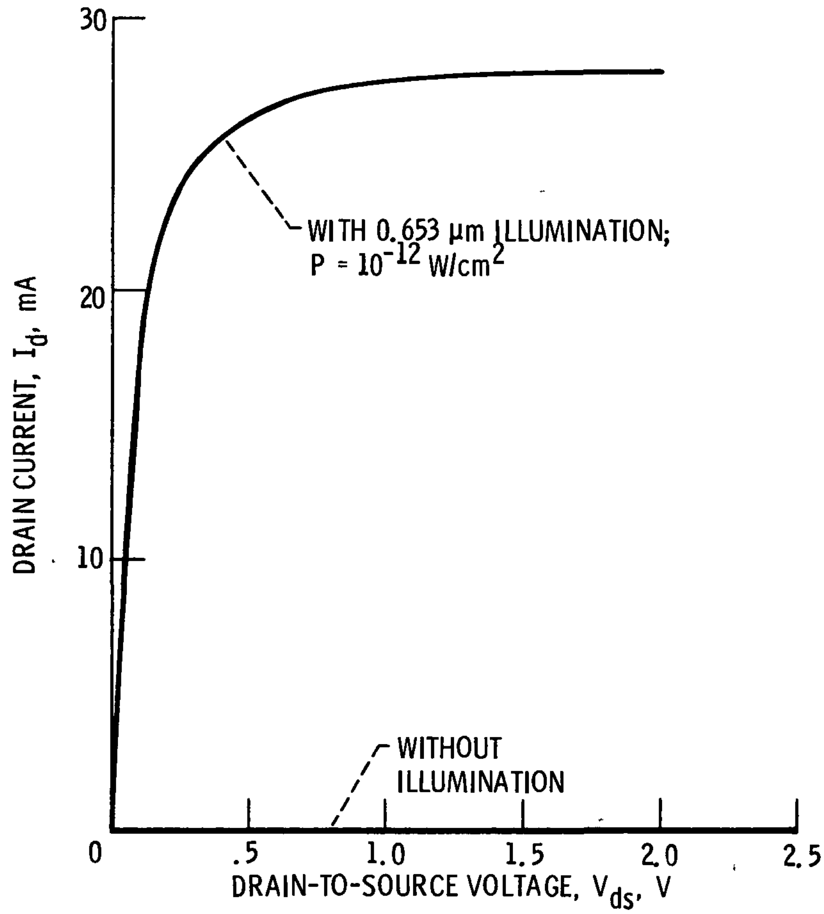


Fig. 8. - Drain current versus the drain-to-source voltage of a depletion-mode (normally on) AlGaAs/GaAs HEMT. Gate bias voltage, V_{gs}, - 0.65 V.

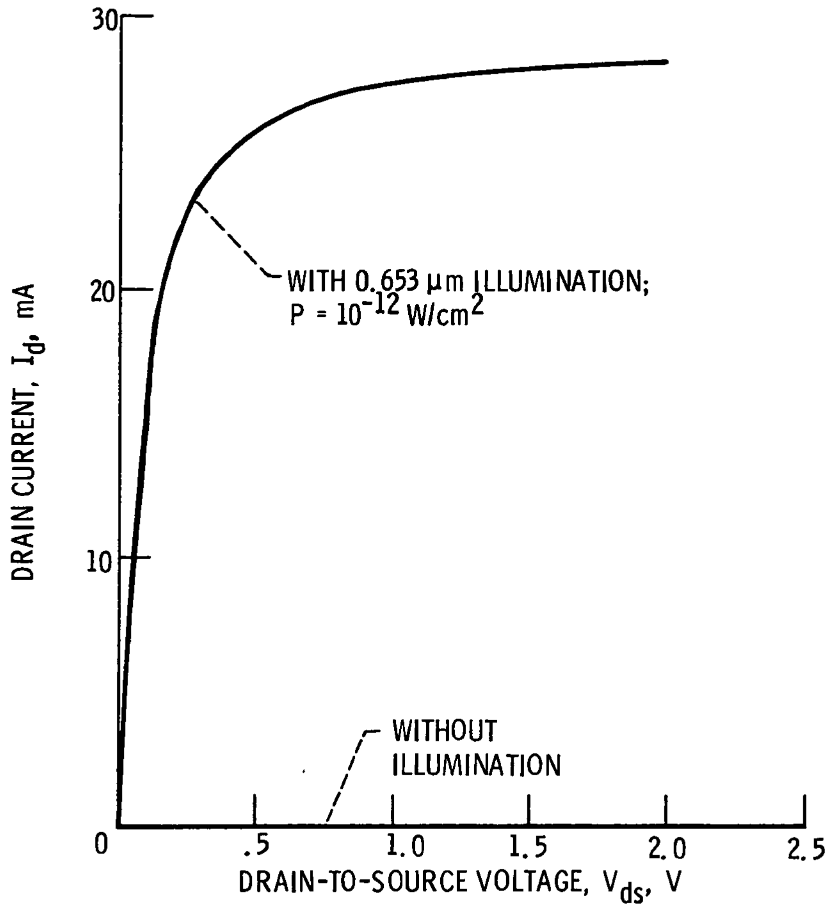


Fig. 9. - Drain current versus the drain-to-source voltage of an enhancement-mode (normally off) AlGaAs HEMT. Gate bias voltage, V_{gs}, 0.

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15 Supplementary Notes

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16 Abstract

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