# Optical Control of a Backside Illuminated Thin-Film Metamorphic HEMT

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***One of the aspects of the merging of microwave and optical technologies is the use of optical signals to switch electronic circuits in general and microwave circuits in particular. It is shown in this paper how a thin-film M(etamorpic) HEMT can be used as a photosensitive component. The advantage of this novel approach is the possibility of illuminating the backside of the thin (2-3 μm) device. The contact metal (of gate, source and drain) is not hindering the light, penetrating into the semiconductor. The thin-film device has a much larger responsivity than a regular, frontside illuminated device. A test set-up, consisting of a 1550 nm laser and a large signal network analyser, enables us not only to do DC and S-parameter measurements, but also time-domain measurements with a modulated telecom laser source.***

## INTRODUCTION

The metamorphic approach represents an attractive alternative to InP-based electronics and is potentially the lowest cost solution to requirements for next generation applications [1],[2]. In order to reduce costs, IMEC has developed a $In_{.53}Ga_{.47}As/In_{.52}Al_{.48}As$ MHEMT process on cheap Ge (germanium) substrates together with a low-cost MCM-D (Multi-Chip Module-Dielectric) integration technique [3]. This low-cost packaging technique (in contrast to a more expensive MMIC solution) enables us to develop integrated modules of electronic and optical components on a hybrid glass substrate. In this way, hybrid circuits, consisting of active and passive components and operating at frequencies above 50 GHz have been demonstrated [4]. IMEC has developed a selective substrate removal technique for Ge. This technique enables us not only to integrate these MHEMTs in the hybrid MCM-D package but also to improve the RF performance of the devices drastically [5]. As a first step to our final goal of an optoelectronic hybrid circuit, we have investigated the sensitivity to light of a thin-film device (Figure 1), compared to regular MHEMTs. The optical responsivity of this thin-film device under backside illumination is not limited by shadowing effects of the contact metal. Illuminating the active region has the same effect as forward biasing the gate [6]. Direct optical control of microwave semiconductor devices has been an area of growing interest since many years. Various RF control functions including gain control of amplifiers, oscillator tuning, locking and frequency modulation, switching, mixing, limiting and phase shifting have already been demonstrated [7][8]. The use of optical signals to control or introduce signals directly into microwave devices has several advantages. First, no extra electronic circuits are required to process the detected signals before application to the microwave device. Second, an extra control port is available to devices that are difficult to control electrically. Third, the optical control signal is immune to electromagnetic disturbances.

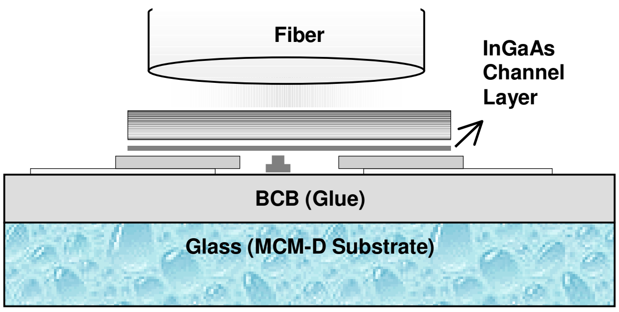


*Figure 1: Schematic Cross-section of a Thin-Film MHEMT under Illumination*

## THEORY

Three physical effects occur in a InGaAs/InAlAs HEMT illuminated by a 1550 nm laser :the photoconductive effect, the internal and the external photovoltaic effect [9]. The photoconductive current is due to excess carriers in the active channel. The internal photovoltaic effect (backgating) results from photogenerated holes drifting towards the GaAs buffer layer, causing a positive charge build up in the substrate/source electrode contact. Charge neutrality is maintained by drawing electrons in from the source contact. Large optical response can be achieved by introducing a large resistor (typically around 1 MΩ) in the gate circuit, thus utilizing the optically induced gate current to generate photovoltage across the gate junction, which causes change in the drain current. This is the external photovoltaic effect. The photovoltaic effect is characterised by a large gain and a logarithmic variation of the photoresponse with light intensity [10],[11].

## DC AND S-PARAMETER MEASUREMENTS

### Experimental Set-Up

In order to perform on-wafer RF measurements of top-illuminated devices in combination with an analytical probe station, we have used a lightwave probe. Furthermore, the set-up consists of a vector network analyser, a telecom laser module, laser mount and controller. The modulation bandwidth of the mount is specified from 10 MHz to beyond 2.5 GHz. The laser, emitting at a wavelength of 1550 nm, is a standard light source for high-capacity long-haul optical transmission systems. The maximum optical output power is 10 mW. A standard optical connector connects the laser's fiber with the lightwave probe. In order to provide precise illumination of ultra-high speed devices we have used a 5 μm diameter lensed fiber launch end. The MHEMT devices we have used for the measurements have a gate length of 0.2 μm and a gate width of 100 μm.

### DC Measurement Results

DC measurements have been performed, clearly indicating the high sensitivity to light of this thin-film transistor. The thin-film device can be illuminated from the backside through the InAlAs metamorphic buffer layer under the active channel. This InAlAs layer has a large bandgap and does not absorb light at 1550 nm. In this way, the gate metal is not hindering the light, penetrating into the semiconductor. Frontside illuminated devices suffer from shadowing effects of the contact metal, limiting the responsivity. The area in between source and drain regions is only 1.5 μm by 100 μm large, almost half of this region (0.7 μm by 100 μm) lies in the shadow of the top of the T-gate metal. Another interesting feature of backside illumination is that the optical signal only has to travel through a thin InAlAs layer to interact with the active layers. Any light not absorbed by the active layer during the initial trip is absorbed after reflection from the contact metallization, resulting in higher coupling efficiency [12]. This clearly shows the advantages of the Ge substrate removal technique and the potential for MCM-D integration in applications with optically controlled FETs.

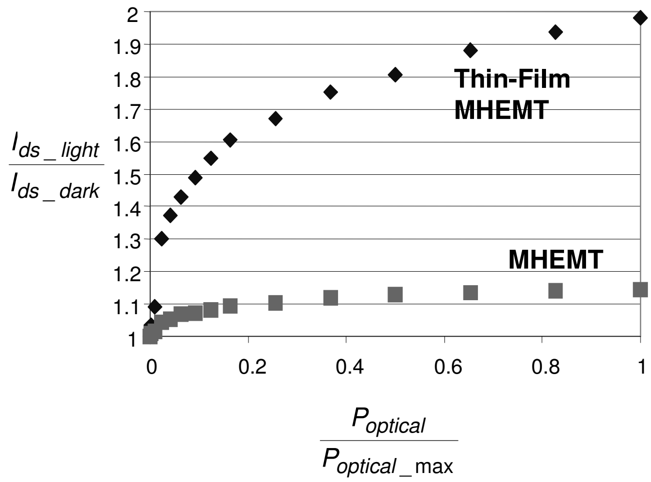


*Figure 2:Comparison of Photoresponse of a Thin-Film MHEMT (backside illuminated) and a regular MHEMT (frontside illuminated)*

Figure 2 shows a comparison of the drain photoresponse as function of light intensity of a thin-film MHEMT and a regular MHEMT (both have been biased near pinch-off). The photoresponse is logarithmic with respect to the optical power (photovoltaic effect). The photoconductive effect would predict a linear relationship between photoresponse and optical power. When biased at a gate voltage of 0 V, an increase in $I_{ds}$ of 3 mA can be measured under backside illumination. The maximum transconductance ($g_m$) of the transistor also increases under illumination due to a reduction in source resistance combined with a decrease of the effective channel thickness. These measurements have been performed without an external resistor in the gate circuit.

### S-Parameter Measurements

In order to examine the microwave performance of the thin-film devices under optical illumination, S-parameter measurements up to 50 GHz have been performed. A current bias (at maximum $G_m$) has been applied to the gate instead of the usual voltage bias. The current source has an intrinsic impedance of about 1 MΩ. In this way, a photovoltage can be developed at the Schottky gate. The maximum available gain (MAG) is almost unaffected by optical illumination. The current gain ($h_{21}$) however, increases by a few dB due to the light. The maximum oscillation frequency ($f_{max}$) and current gain cut-off frequency ($f_T$) obtained by extrapolating the MAG and $|h_{21}|$ curves, respectively, show that $f_{max}$ (about 125 GHz) is almost insensitive to optical illumination, but $f_T$ increases from 76 GHz in dark to 84 GHz under illumination. Figure 3 and 4 show the 4 S-parameters of a thin-film device in dark and under illumination. $S_{21}$ clearly increases under illumination, $S_{11}$, $S_{12}$ and $S_{22}$ slightly decrease. It is important to note that the phase of $S_{21}$ is insensitive to illumination.

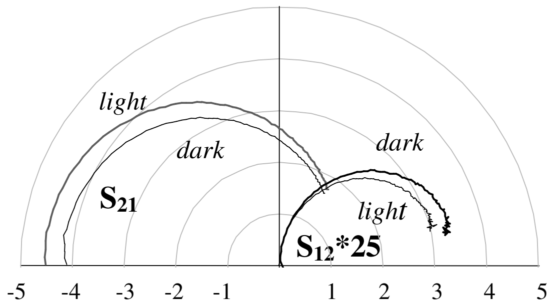


*Figure 3: $S_{21}$ and $S_{12}$ of a Thin-Film MHEMT on a Polar Plot*

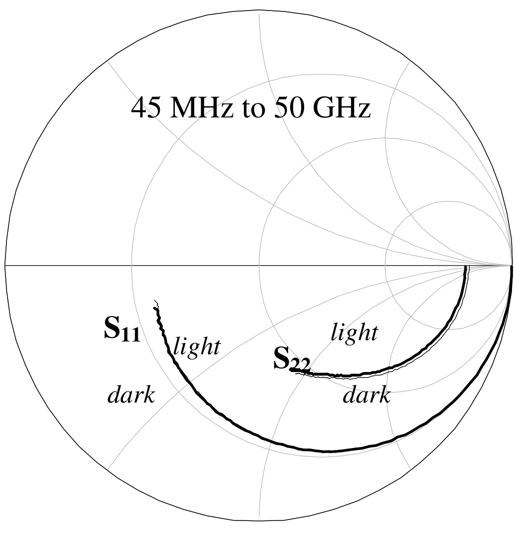


*Figure 4: $S_{11}$ and $S_{22}$ of a Thin-Film MHEMT on a Smith Chart*

## TIME AND FREQUENCY DOMAIN MEASUREMENTS

### Measurement Set-Up

In order to perform measurements both in time and frequency domain, we have extended the set-up with Agilent's large-signal network analyser (LSNA) [13]. This non-linear network measurement system, generally used to perform vectorial, large-signal measurements, is able to measure incident and scattered waves at the input and output of an electrical microwave device simultaneously, both in amplitude and phase. The system measures the fundamental frequency and several harmonics at the ports of the device under test (DUT). The system's frequency range is 600 MHz up to 20 GHz. The amplitude and phase information enables us to reconstruct a signal's time-domain waveform. In order to measure the absolute waveforms at the DUT's output port, the non-linear network measurement system requires an absolute electrical calibration. The laser has been modulated by an external RF source. The RF power of the source has been set at 17 dBm for these measurements. Phase coherence between the LSNA and the external source is accomplished by synchronizing the AD converters of the LSNA with the 10 MHz reference signal of the RF source.

### Time and Frequency Domain Measurement Results

The RF (sine wave) source has been used to directly modulate the laser at frequencies between 600 MHz and 4.2 GHz. The time domain waveforms of the drain and gate current and voltage have been measured. The transistor has been biased at $V_{ds}$ = 0.7 V, a current bias has been applied to the gate. The measured signals ($i_{ds}$and $v_{ds}$) clearly show the sine wave modulation. Due to the the transistor's gain effect the modulation current signals at the drain are about 30 dB larger than at the gate. These signals have also been measured in the frequency domain. Between 600 MHz and 2.4 GHz, the amplitudes of the drain current modulation signals ($i_{ds}$) decrease by approximately 6 dB/octave corresponding to the transistor's photovoltaic effect. Figure 5 shows the measured time domain waveforms of the transistor's drain voltage, figure 6 shows the measured frequency domain drain current signals. The light has been modulated at 600 MHz, 1.2 GHz, 1.8 GHz and 2.4 GHz. When comparing the $i_{ds}$ signals at 3, 3.6 and 4.2 GHz however, we notice a much larger decrease than 6 dB. This is due to the bandwidth limitation of the laser mount. In all cases, higher harmonic signals are negligible.

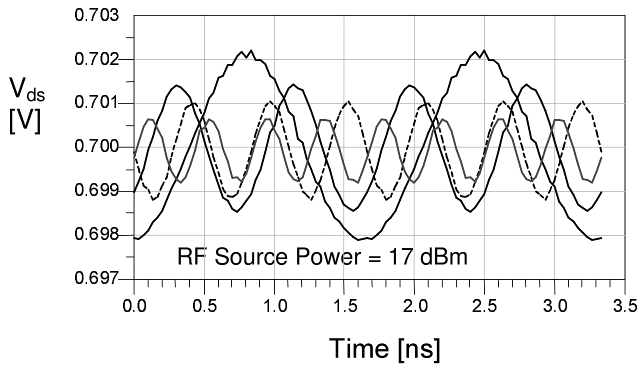


*Figure 5: Time Domain Voltage Waveforms at Transistor's Drain (0.6, 1.2, 1.8, and 2.4 GHz)*

Finally, we would like to note that the transistor's output signal is very sensitive to the position of the fiber above the active area. The lensed fiber output with a minimum illumination diameter of 5 µm is not an optimum solution for illuminating the 1.5 µm by 100 µm active region.

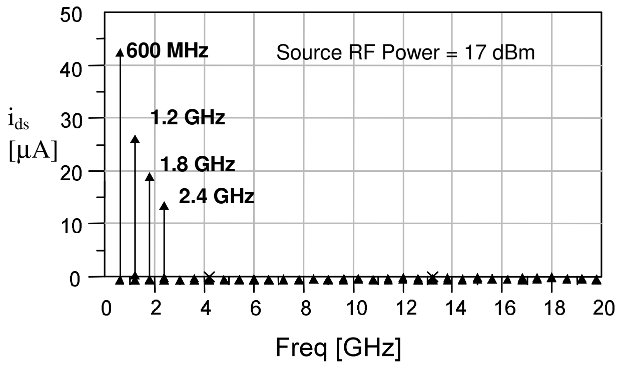


*Figure 6: Frequency Domain Drain Current Signals*

## CONCLUSIONS

Direct optical illumination of active devices has been an area of growing interest for many years. In this paper, we have shown that a microwave device, a thin-film MHEMT, excited by a modulated optical source can be characterised in time and frequency domain by a non-linear network measurement system. This thin-film device shows a high responsivity due the possibility of backside illumination. Modulation signals up to 3.6 GHz have been measured with our set-up, turning the thin-film microwave device into a gigabit photodetector.

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