

STATIC AND DYNAMIC CHARACTERIZATION OF HIGH SPEED HMSM PHOTODETECTOR FOR SHORT HAUL COMMUNICATIONS

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Abstract – A novel RCE (Resonant-Cavity- Enhanced) HMSM (Heterostructure Metal-Semiconductor-Metal) photodetector with AlGaAs distributed Bragg reflector is analyzed. The effect of the two dimensional electron gas (2DEG) in the GaAs absorption layer has been evaluated by comparing two samples, the first with a delta doped sheet in the upper AlGaAs layer, and the second with undoped AlGaAs. The I - V curve shows that there is a very low dark current (around 10 pA at high bias) and a value of 20 μ A at high bias voltage in DC photocurrent, under 497 μ W optical power laser illumination. C - V measurements highlight very low capacitance values, in agreement with the calculated geometrical ones. The photocurrent spectrum shows a clear peak at 850 nm wavelength with full width at half maximum (FWHM) of around 30 nm, while time response measurement gives a 3 dB bandwidth of about 34 GHz. Combination of very low dark current and capacitance, fast response, wavelength selectivity, and compatibility with high electron mobility transistors makes this device especially suitable for short haul communications purposes.

Keywords: Heterostructure, Metal-Semiconductor-Metal, Photodetectors, Distributed Bragg Reflector.

1. INTRODUCTION

Schottky photodiodes based on heterostructures are very attractive for high-speed photodetection because of their superior performance in terms of low noise, transient response, photocurrent spectrum and monolithic optoelectronic integration. In addition, resonant cavity-enhanced (RCE) photodetectors have attracted much attention in the past few years due to their potential in solving the trade off between high quantum efficiency and high speed while, at the same time, offering narrow spectral bandwidth detection [1]. On the other hand, in today's lightwave communication systems, optoelectronics receivers are realized by monolithic integration of compatible photodetectors and transistor amplifier circuits, so the fabrication and characterization of such low-noise, high speed receivers play an important role having a tremendous technological impact [2].

In this article we discuss a GaAs-based high-speed, resonant-cavity-enhanced, heterostructure metal-

semiconductor-metal photodetector with $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ distributed Bragg reflector operating around 850 nm. The top reflector is a delta modulation doped $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ that also acts as the barrier enhancement layer thus providing very low dark current values. We have previously proposed AlGaAs/GaAs heterostructure metal-semiconductor-metal photodetectors (HMSM-PD's) that show much less dark current than conventional MSM due to both the two dimensional electron gas (2DEG) and the effect of barrier enhancement due to the wide-gap material [3, 5, 6]. The beneficial effect of the doping of the wide gap material is also observed in the present work, where we compare the properties of the devices with and without delta-doping in the wide-gap material.

2. DEVICE STRUCTURE

A schematic cross-section of the grown RCE heterojunction MSM is shown in Figure 1. The layer structure was grown by solid-source molecular beam epitaxy on a semi-insulating GaAs substrate. Twenty periods $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ DBR were grown on 200 nm GaAs buffer layer. The bottom mirror was designed for high reflectance at 850 nm center wavelength. The thickness of the top barrier enhancement layer is 50 nm and the spacer layer is 5 nm. A Si delta (δ)

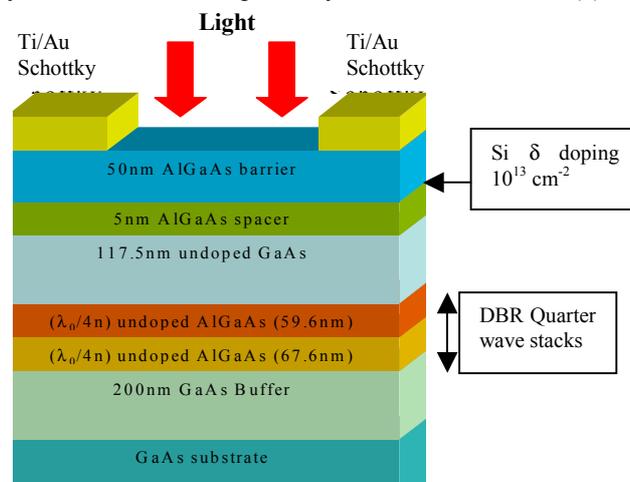


Fig. 1. Device structure of the resonant-cavity-enhanced HMSM photodetector.

doped layer with sheet density of 10^{13} cm^{-2} was grown between barrier enhancement and spacer layers. The device area was $40 \times 40 \mu\text{m}^2$ with a typical interdigital pattern with finger width of 1 or 2 μm and distance of 2 or 4 μm . For comparison, a device having the same growth structure but without Si δ -doping has been fabricated [7].

Since both contacts are rectifying and symmetric, application of voltage reverse-biases one junction and slightly forward biases the other. The reverse biased junction determines current flow while the other mainly controls electron collection. The barrier between metal and AlGaAs thus dominates current flow. This configuration is useful in the study of leakage gate currents in HEMTs, but has strong application to photodetectors that employ barrier enhancement layers for reduction of dark current. An obvious advantage of this structure is monolithic integrability of the detectors and transistors in both growth and processing that makes it suitable for integrated optical detection applications.

3. EXPERIMENTAL RESULTS

Fig. 2 shows I - V curves under dark and under dc light excitation at two different optical powers for the devices with and without δ -doping.

Under dark, the doped sample shows a soft increase of the current with voltage, with values, at 20 V, lower than 30 pA. The behavior of the undoped sample is rather different, as the current strongly increases at low voltage (2-3 V) up to about 30 pA. As the voltage is raised, current slowly increases up to almost 100 pA at the maximum voltage.

It is worthwhile to note that the lower values of the doped sample are in qualitative agreement with the effect of the repulsion between the electrons in the metal contact and the electrons in the 2-DEG. This effect has been already observed in similar photodetectors realised with uniform doping of the wide-gap material [6].

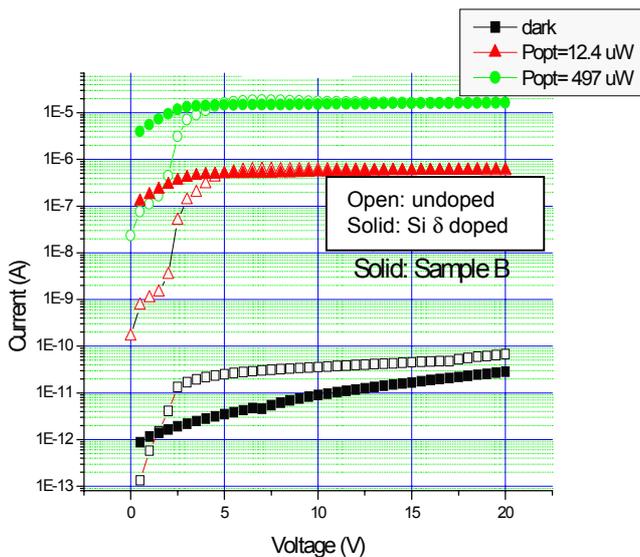


Fig. 2. Comparison of I - V behavior between the delta-doped and undoped devices.

As the voltage increases, the electrons of the 2DEG are pushed away from the contact and the repulsive effect decreases, thus allowing for an easier thermionic emission across the Schottky barrier. As a result, the current increases with the voltage. On the contrary, in the undoped sample there is no 2DEG below the Schottky contact and therefore, is only the blocking effect of the Schottky barrier which determines a constant current, independent of the voltage, but higher than in the previous case due to the lack of repulsive effect.

The light response has been measured by using a 850 nm pigtailed laser, with the optical fiber of 9 μm core positioned just in proximity, but not perpendicularly, of the active area of the device. Due to the very low leakage current and to the good responsivity, both detectors show a large dynamic response, the undoped samples showing lower photocurrent values at low voltage. However, for $V > 2-3 \text{ V}$, the photocurrent curves of both samples merge and strongly saturate. Saturation indicates that complete collection of the photo-generated carriers occurs.

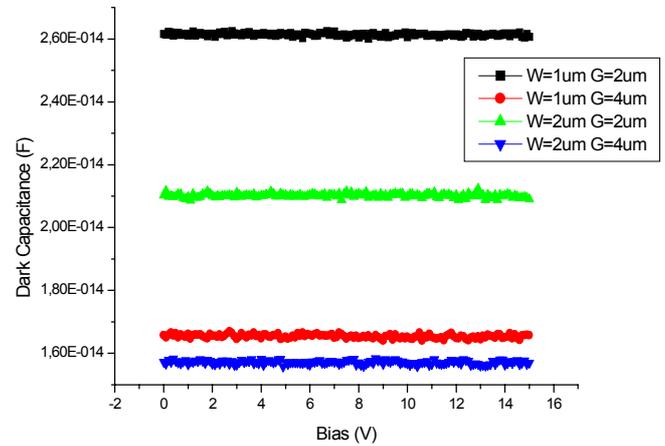


Fig. 3. C - V curves for four different interdigital structures of δ doped device.

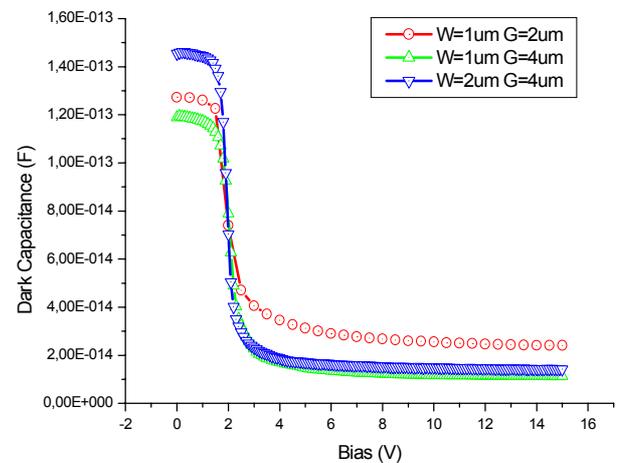


Fig. 4. C - V curves for three different interdigital structures of undoped device.

By using a precision LCR meter, we also performed capacitance measurements at 1 MHz frequency and 30 mV amplitude of the oscillating voltage as a function of the constant applied voltage, on doped and undoped devices. The measurements have been carefully carried out paying attention to the sample shielding, minimizing cable length, and subtracting the stray capacitance.

The C - V curves of samples having different contact finger width (W) and inter-finger distance (G) are reported in Fig. 3 and Fig. 4 for the doped and undoped devices, respectively. The most evident and surprising feature is that doped samples show capacitance values independent of the applied voltage, while the undoped samples show at low voltage much higher values, even one order of magnitude greater than the high voltage value. For these samples, the capacitance stays almost constant up to almost 2 V and then it decreases suddenly to a constant high voltage value. We note here the strong correlation with the I - V behavior: the capacitance decrease occurs at the same voltage than the current saturation.

We observe in Table I the good agreement between the capacitance values measured at high voltages and those calculated according to the equation which predicts the geometric capacitance of the interdigitated planar devices[4]:

$$C \approx \frac{\pi \epsilon_s A}{2(W+G) \log(2(1+\sqrt{K})/(1-\sqrt{K}))} \quad (1)$$

where ϵ_s is the GaAs permittivity, A is the active area ($1600 \mu\text{m}^2$), and $K = [1 - \tan^4(\pi W / 4(W+G))]^{1/2}$ is a dimensionless quantity which depends on W and G .

TABLE I. Measured and theoretical capacitance values

Interdigital Structure	δ doped sample C (fF)	Undoped sample C (fF)	Calculated values C (fF)
$W=1\mu\text{m}$ $G=2\mu\text{m}$	24,4	26	27
$W=1\mu\text{m}$ $G=4\mu\text{m}$	11,5	16,5	13
$W=2\mu\text{m}$ $G=2\mu\text{m}$	-	21,5	26,5
$W=2\mu\text{m}$ $G=4\mu\text{m}$	14,4	16	14

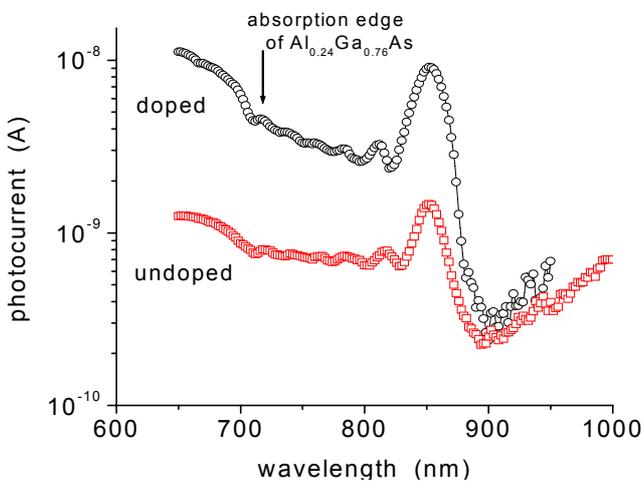


Fig. 5. Photocurrent spectral response for doped and undoped devices.

Fig. 5 illustrates the experimental photocurrent spectral response of the doped and undoped RCE-HMSM photodetectors. A monochromator with 0,15 nm resolution was used to select the excitation wavelength from a chopped tungsten light source. The signal was measured by a lock-in amplifier and the spectral response was measured under 10 V reverse bias. The resonant peak is around 850 nm and the FWHM value is 30 nm. An increase of photocurrent is observed around 710 nm, which is due to absorption in AlGaAs layers. We note that the spectral response is, at all the wavelengths, much higher for the doped than for the undoped device. This is consistent with the photocurrent response to the monochromatic laser at 850 nm (Fig. 2), by taking into account that in Fig. 5 the light intensity is pretty low and the applied voltage is 10 V. Some photocurrent oscillations are evident between 720 nm and 850 nm in both devices which can be attributed to the effect of the Bragg reflector.

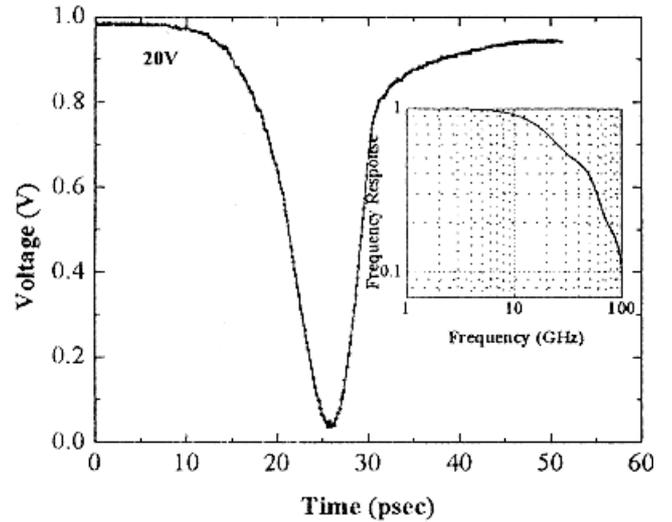


Fig. 6: Temporal response of photodetector, insert shows the calculated frequency response

High-speed time measurements were made using a mode-locked Ti Sapphire laser, operating at a repetition rate of 76 MHz that generates 125 fs pulses. We have selected the wavelength of the tunable laser at 850nm and we have used an average optical power of 0,1 mW which corresponds to a pulse energy of about 1,4 pJ. The optical pulses impinge on the photodiodes biased through a bias tee. The photodiode RF signal is measured on-wafer with a 50GHz sampling oscilloscope. Fig. 6 shows the temporal response of a doped photodetector with a 1 μm finger and 4 μm spacing between fingers, measured at 20 V bias. From the figure, FWHM of the time response is 8,1 ps, its rise time is 8,8 ps, and fall time is 9 ps. Fast Fourier Transform of the data is shown in the inset of figure and has a 3 dB bandwidth of 34 GHz. The fact that rise time, fall time and FWHM of the peak are all comparable suggests that the electrical circuit limits somehow the speed of response as measured by the oscilloscope. In order to check the reliability of the measurements, we have carried out measurements over all the devices of different contact

geometry, both doped and undoped. The results are summarized in Table II which reports, for all the investigated samples, the amplitude and FWHM of the peak, obtained at 20 V bias. The peak amplitude has been properly normalized to take into account the active area of the device. The results are all self-consistent showing that:

- The doped samples have peak amplitude always greater than the undoped samples. This result, which refers to the dynamic response confirms the photocurrent measurements carried out under static conditions.
- The samples with $G=2 \mu\text{m}$ have peak amplitude always greater than those with $G=4 \mu\text{m}$, for each W . This result is indicative of incomplete collection of charge, probably due to trapping processes.
- The pulse widths of the undoped samples of different W and G are comparable among them; the same holds for the doped samples (except one). More, the doped samples have peak widths shorter than undoped samples. Even in this case, doped samples show better performance than the undoped ones since the shorter pulse width means a higher detector bandwidth. It is quite surprising that the detectors showing higher responsivity also show faster response, as the two figures of merit go usually in opposite directions.

TABLE II. Peak amplitudes and widths of the temporal response of the doped and undoped devices biased at 20 V, for different dimensions of the interdigitated contacts.

Width, gap (μm)	δ -Doped		Undoped	
	Amplitude (a.u.)	Width (ps)	Amplitude (a.u.)	Width (ps)
W=1,G=2	0,331	7,97	0,192	9,45
W=1,G=4	0,252	7,03	0,103	10,16
W=2,G=2	0,292	11,9	0,207	10,38
W=2,G=4	0,206	7,11	0,111	12,04

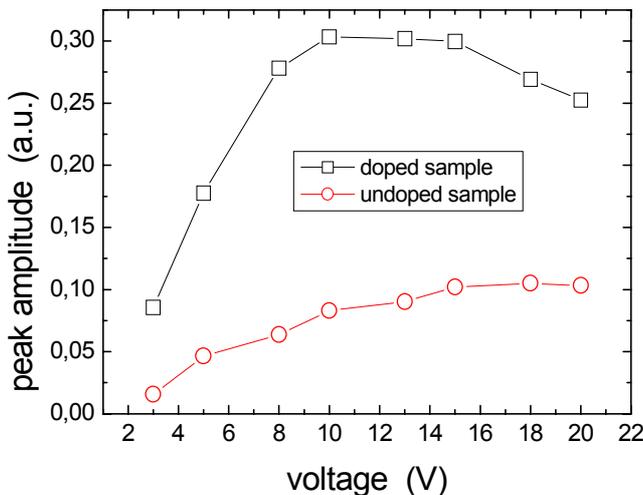


Fig. 7. Peak amplitudes as function of the applied voltage, for the doped and undoped samples with $W=1$, $G=4$.

In Fig. 7 we report the peak amplitude of the induced pulses as a function of the applied voltage. The doped sample shows a steep increase of the amplitude, then a saturation around 10 V and finally, for $V > 15$ V a slight decrease. The undoped sample shows lower values which tend toward saturation around 18 V.

4. CONCLUSIONS

In conclusion we have characterized a HMSM Schottky photodetector, and we have demonstrated the performance improvement due to a resonant-cavity-enhanced. In fact, the suitable employment of the vertical resonance cavity is useful in solving the trade off between high quantum efficiency and high speed while, at the same time, offering narrow spectral bandwidth detection. In addition, the presence of a δ doped sheet in the upper AlGaAs layer, plays an important role, in terms of barrier enhancement and internal electric field aiding in transport of photocarriers.

The two devices exhibited very low dark current and capacitance, wavelength selectivity, high quantum efficiency. High speed time response data indicates that the devices easily operate in tens of Gigahertz with the δ doped device showing much higher peak of response with no adverse effect, even slight improvement, of rise time and FWHM.

Combination of low dark current and capacitance, fast response, wavelength selectivity and integrability with high electron mobility transistors makes this device especially suitable for short haul communications purposes. Based on this evaluation, we suggest that this heterojunction based device that uses the same technology as the HEMT is an excellent candidate for Gigabit Ethernet, 10 Gigabit Ethernet, OC 48 and OC 192 applications.

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