An Investigation of the Effect of Schotky Barrier-Height Enhancement Layer on MSMPD Dynamic Characteristics

Jong-Wook Seo

Abstract— **The effect of the wide-bandgap Schottky barrier enhancement cap layer on the performance of metal-semiconductor-metal photodetectors (MSMPD's) is presented. Judged by the dc characteristics, no considerable increase in recombination loss of carriers is resulted by the incorporation of the cap layer. However, about 45 % of the detection efficiency is lost for the cap-layered MSMPD's even with a graded layer incorporated under pulse operation, and it was found to be due mainly to the capturing and slow release of the photocarriers at the heterointerface. The loss mechanism of the pulse detection efficiency is believed to be responsible for the intersymbol interference and the increased bit-error-rate (BER) observed in MSMPD's when used with a high bit rate pseudo-random-bit-stream (PRBS) data pattern.**

Index Terms — MSMPD, responsivity, Schottky barrier, heterojunction, efficiency.

I. INTRODUCTION

Since the MSMPD has a planar structure and compatibility with field-effect transistor (FET)-based electronics, it has been developed into one of the most promising photodetectors for optoelectronic integrated circuit (OEIC) applications [1]. However, the formation of stable Schottky contacts with large barrier heights has always been a difficult task particularly for MSMPD's with narrow-bandgap light-absorption layers. The dark current of an MSMPD is determined by the barrier heights at the electrode-semiconductor Schottky contacts, and the barrier heights for electrons and holes add up to the bandgap energy of the semiconductor [2], [3]. Therefore, an epitaxially grown wide-bandgap cap layer is commonly incorporated on top of the absorption layer to enhance the Schottky barrier height for both carriers [2].

The incorporation of the cap layer, however, introduces potential barriers, and some of the carriers are captured at the heterojunction between the cap layer and the absorption layer. It has been reported that signal distortion or carrier loss can result from the carrier pile-up at the interfaces [4]. Although it has been believed that the incorporation of a graded layer can reduce the carrier trapping, the effectiveness of the graded layer insertion has not been studied much. It has also been reported that the operation of an MSMPD at high frequency region, compared to a *p-i-n* photodetector, is dominated by the intersymbol interference when used with a PRBS data [5]. In this letter, the effect of the cap layer on the performance of MSMPD's operating in dc- and particularly pulse-operation conditions is studied. The effect of carrier capturing at the heterointerface is studied quantitatively. Since GaAs has a wide enough bandgap to provide a low dark current, GaAs MSMPD's

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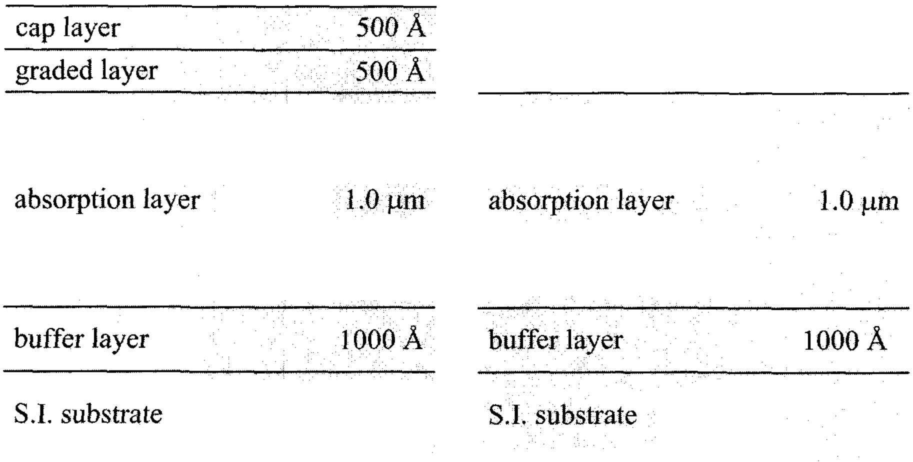
with and without a cap layer are studied comparatively.



(a) (b)

Fig. 1. The layer structures of MSMPD's (a) with and (b) without a cap layer.

II. EXPERIMENT

In this work, the heterostructures utilized for a cap-layered MSMPD incorporates four main layers grown by molecular-beam-epitaxy (MBE) on semi-insulating substrates. The heterostructure specifically consists of a buffer layer, an absorption layer, a graded layer, and a cap layer as shown in Fig. 1(a). An MSMPD without a cap layer consists only of a buffer layer and an absorption layer as shown in Fig. 1(b). The thickness of the GaAs and the $In_{0.53}Ga_{0.47}As$ absorption layers was chosen to be 1 μm, which should absorb approximately 80 % of the incident optical power at wavelengths of 0.85 and 1.3 μm, respectively [6], [7]. The $Al_{0.3}Ga_{0.7}As$ and $In_{0.52}Al_{0.48}As$ cap layers have a thickness of 500 Å, and linearly graded $Al_xGa_{1-x}As$ and In(Al,Ga)As layers with a thickness of 500 Å were incorporated underneath the cap layers, respectively. The Ti/Au metal electrodes with finger dimensions (width/gap) of 1 μm/1 μm and 2 μm/2 μm were finally patterned using the lift-off method, and the MSMPD's have a detection area of 50 x 50 μm^2.

The dc characteristics of the MSMPDs were tested using a Hewlett-Packard HP 4142B semiconductor parameter analyzer and an HP 8153A lightwave multimeter. An HP 81552SM laser source and an HP 81531A power sensor module were used for the measurement of the InGaAs MSMPD working at λ=1.3 μm, and an HP 81551MM laser source and an HP 81530A power sensor module were used for the GaAs and AlGaAs MSMPDs operating at λ=0.85 μm. An optical beam from a laser source illuminates the device under test through an optical fiber and a microscope. The test set-up enabled the incident optical beam to be confined within the active area of the detector. The optical power incident upon the detector was calibrated using an Epitaxx EXT-2000T5 photodiode and an HP 81531A power sensor for the 1.31 μm wavelength; while an Antel AS7025 photodiode and an HP 81530A power sensor were used for the 0.85 μm wavelength.

The pulse responses of the detectors were characterized by time-domain measurement using optical pulse streams from optical impulse generators. Short- and long-wavelength pulses with a repetition rate of 1 MHz were delivered by the Tektronix OIG-501 and OIG-502 impulse generators, respectively. The optical pulses had pulse-widths (full-width at half-maximum) of 33 and 37 psec, and average powers of 882 and 212 nW at wavelengths of 0.85 and 1.3 μm, respectively. The electrical response pulse from the detector was decoupled by the bias-T to the Tektronix 11802 digital sampling oscilloscope through a SD30 sampling head.

III. DISCUSSIONS

Fig. 2 shows the measured detector internal efficiencies of the MSMPD's as functions of incident

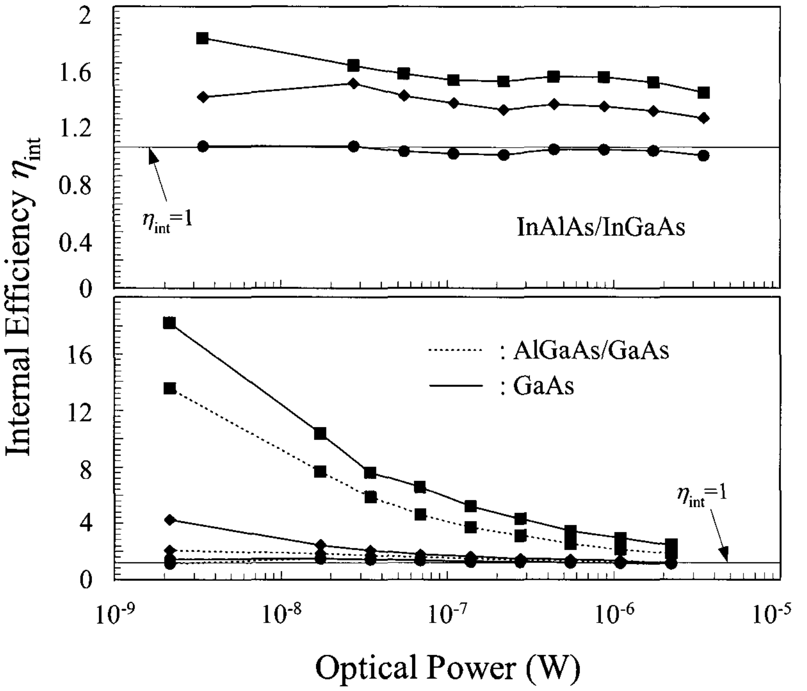


Fig. 2. Detector internal efficiency versus incident optical power for the GaAs, AlGaAs/GaAs, and InAlAs/InGaAs MSMPD's under dc operation condition at several applied voltages (●: 2 V, ♦: 5 V, ■: 10 V).

optical power for several bias voltages under a dc operation condition. The internal efficiency η_{int} is defined as the ratio of the number of detected photocarriers to the number of photons absorbed in the detector absorption region:

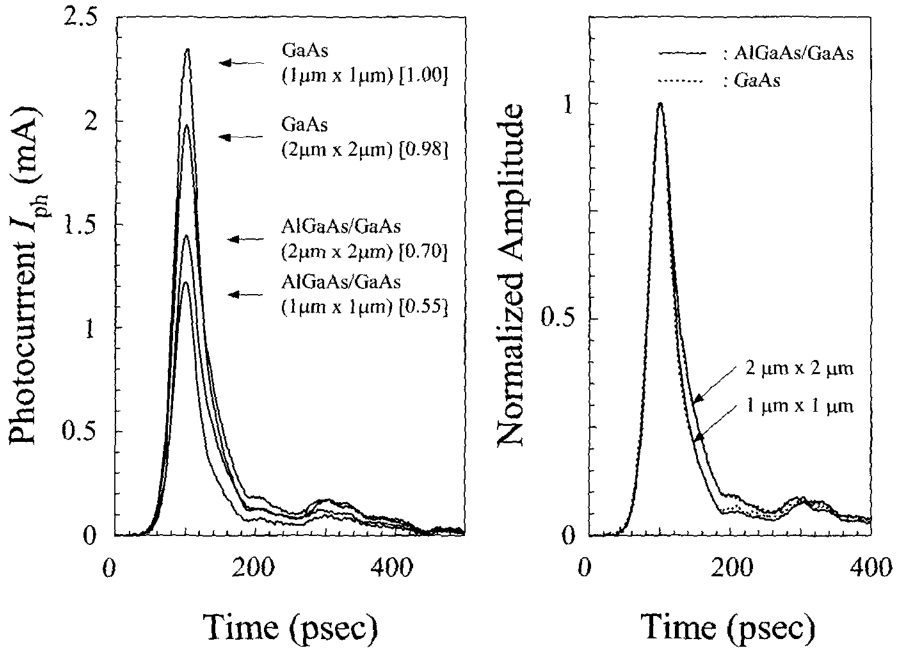
$$\eta_{\text{int}} = \frac{1}{\eta_{ext}} \frac{hc}{q\lambda} R_{dc} \qquad (1)$$

where

$$R_{dc} = \frac{I_{ph}}{P_{opt}} \qquad (2)$$

is the detector dc responsivity, P_{opt} is the power of the incident light, I_{ph} is the photocurrent, and η_{ext} is the detector external-quantum-efficiency (EQE) that is defined to be the ratio of the number of the photons absorbed in the detector absorption region to the number of photons incident upon the detector. The EQE's are estimated based on the device geometry to be approximately 0.3 for the MSMPD's used in the study. It can be seen from the figure that the dc internal efficiencies asymptotically approach the theoretical limit of 1.0 as the light intensity is increased. Additionally, the efficiencies of the GaAs and AlGaAs/GaAs MSMPD's are almost identical at 1 V $\leq V_{\text{bias}} \leq$ 3 V, where the current gains are low. Therefore, it can be concluded that the loss of carriers by recombination is not significant even for an MSMPD with a cap layer.

Fig. 3(a) shows the pulse responses of the GaAs and AlGaAs/GaAs MSMPD's measured at V_{bias} = 10 V. The waveforms represent the current across a 50 Ω load resistance. The numbers in square brackets are the areas under the waveforms ratioed to that of the 1 μm/1 μm GaAs MSMPD. Since the duty ratio of the input optical pulse stream is so small (33 psec/1.0 μsec = 3.3×10^{-5}), the instantaneous input power level of the optical signal is high (882 nW/3.3×10^{-5} = 26.7 mW) enough to assure the detectors to operate in the region where the current gain is negligible. Without the gain, the below-unity area factors of the response curves imply that some of the internal efficiencies are lost even though no carriers are lost by recombination as mentioned previously. In the mean time, no significant difference in pulse shape was found among the detectors with the same electrode geometry as can be seen from the Fig. 3(b).



(a) (b)

Fig. 3. Pulse responses of GaAs and AlGaAs/GaAs MSMPD's measured at V_{bias}=10 V. (a) Photocurrent across a 50 Ω load resistance, (b) Pulse waveforms normalized to have a unit amplitude.

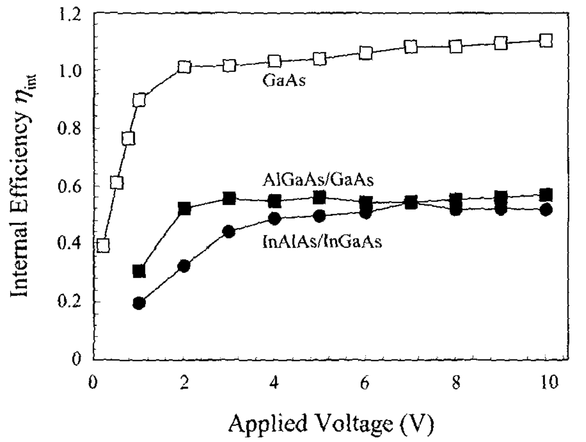


Fig. 4. Detector internal efficiencies of the GaAs (□), AlGaAs/GaAs (■), and InAlAs/InGaAs (●) MSMPD's under pulse operation condition as a function of applied voltage. The 1 MHz optical pulse streams have average powers of 882 and 212 nW at 0.85 and 1.3 μm wavelengths, respectively.

Fig. 4 shows the internal efficiencies of various MSMPD's under pulse operation as a function of bias voltage. The internal efficiency is obtained using Eq. (1) by redefining the responsivity given by Eq. (2) as the ratio of the number of photocarriers detected per pulse during the pulse window ($0 \le t \le 500$ psec) to the number of photons absorbed in the absorption region:

$$R_{pls} = \frac{1}{T_{pls}P_{opt}} \int_{window} I_{ph}\,dt = \frac{Q_{pls}}{E_{opt}} \qquad (3)$$

where T_{pls} and P_{opt} are the period and the average power of the optical pulse stream, respectively, E_{opt} is the energy brought by a single light pulse, and Q_{pls} is the total charge detected within the pulse window. As can be seen from the figure, the internal efficiencies of the cap-layered detectors are much lower than that of the detector without a cap layer. About 45 % of the internal efficiency is lost for the 1 μm/1 μm AlGaAs/GaAs MSMPD, and slightly more for the 1 μm/1 μm InAlAs/InGaAs MSMPD possibly due to the larger band discontinuities between the cap layer and the absorption layer. Additionally, it can also be seen that the efficiency of the GaAs MSMPD becomes higher than unity seemingly due to the gain effect while those of the cap-layered detectors are almost independent of the applied voltage above certain voltages.

The loss of the detection efficiency for the cap-layered MSMPD's under pulse operation is believed to be due to carrier capturing at the heterointerface between the cap layer and the absorption layer. In the cap-layered MSMPD's, it is believed that most of the photocarriers are captured at the heterojunction, and the captured carriers are released very slowly to the electrodes compared to the carrier transit time. Since photocarriers stopped on the way induce only a part of the charges they carry, the resulting current in the external circuit will be lower than that corresponding to the complete transit of the carriers [8]. The remaining part of the charges will be induced when the carriers escape to an electrode. However, if the emission delay is much longer than the transit time, the information-carrying pulse properties will be lost to the background as in the case of the cap-layered MSMPD's.

The efficiency loss by carrier capturing becomes clearer if the pulse responses of the MSMPD's with different electrode dimensions are compared. As can be seen from the Fig. 3, the pulse responsivity of the GaAs MSMPD with a finger width/gap of 2 μm/2 μm is slightly lower than that of 1 μm/1 μm detector. This is possibly because of the lower gain and higher recombination loss of the larger-geometry detector due to the weaker electric field and the longer transit distance, respectively. However, the pulse responsivity of the 2 μm/2 μm AlGaAs/GaAs detector is much higher than that of 1 μm/1 μm one. For the AlGaAs/GaAs MSMPD, since the efficiency is rather determined by the rate of charge induction by the captured carriers in the well, the efficiency loss increases as the ratio of the cap layer thickness to the inter-electrode distance is increased. Meanwhile, the slight discrepancy of the efficiency loss from the direct proportionality to the ratio (45 % for 1 μm/1 μm, 30 % for 2 μm/2 μm) is believed to be due to the lateral geometry of the devices.

The capturing of photocarriers is believed to result in the intersymbol interference and the increased BER observed in the cap-layered MSMPD's when used with a PRBS data pattern. Since the dynamic detection efficiency of a cap-layered MSMPD varies with the carrier emission rate from the well, it will be determined by the carrier concentration in the well. The effective barrier height, which determines the emission rate, changes as the quasi Fermi level moves up and down with the variation of the carrier concentration. Consequently, the amplitude and width of a light-ON bit will be dependent on the data pattern because the carrier concentration will be determined by the previously arrived bit pattern. For instance, the amplitude of a bit following a long light-ON inputs may be larger than average whereas that following a long stream of light-OFF inputs will be smaller.

IV. CONCLUSIONS

In conclusion, the effect of the wide-bandgap Schottky barrier enhancement cap layer on the performance of MSMPD's is presented. It was found that the presence of the potential barrier results in a reduction of responsivity under pulse operation even with a graded layer incorporated at the heterointerface. The efficiency reduction was found to be due mainly to the capturing and slow emitting of photocarriers at the heterointerface instead of the recombination loss of the carriers. The carrier capturing is believed to be responsible for the intersymbol interference when used with a high bit rate PRBS data pattern. Accordingly, it is of crucial importance to develop ways to minimize the carrier capturing at the heterointerface in order to improve the performance of MSMPD's particularly for long wavelength applications.

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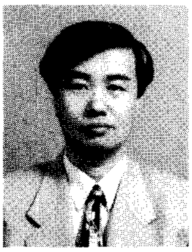

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