InP-BASED MONOLITHICALLY INTEGRATED PHOTORECEIVER FOR 4-10GBIT/S OPTOELECTRONIC SYSTEMS

M. Horstmann, M. Hardtdegen, K. Schimpf, J. Muttersbach, R. Lehmann, M. Marso, and P. Kordoš

Institute of Thin Film and Ion Technology, Research Centre Jülich, D-52425 Jülich, Germany
Phone:+49246161-2064, Fax: +49246161-2940, e-mail: horstman@isitel1.isi.kfa-juelich.de

Abstract - A novel monolithically integrated photoreceiver for 10Gbit/s long-haul optoelectronic transmission systems is presented. The photoreceiver consists of a MSM photodetector and a HEMT amplifier, prepared on an identical InGaAs/InP 2DEG layer structure. The design considerations, preparation procedure and optoelectronic properties of discrete devices and results on a front-end receiver at 1.3μm are presented. The MSM photodetector exhibits a responsivity of 0.21A/W and a 3dB bandwidth up to 16GHz. The HEMT amplifiers have a cut-off frequency f_T of 45GHz and f_{max} of 85GHz. A bandwidth up to 16GHz is achievable on optimized photoreceiver circuits.

I. INTRODUCTION

Monolithically integrated photoreceivers for high speed optoelectronic transmission systems are an important field of research in the last time. Three basic schemes exist for the preparation of monolithically integrated photoreceivers. One method consist of one-step epitaxy, where the detector and the amplifier multi-layered structures are grown in a single epitaxial run. The transistor structure is grown above the detector structure with an insulating layer between the two devices. Although the layers can be optimized for each device, the characteristics have been found to be inferior to discrete processed devices. The reason for this reduced performance is the parasitic electric coupling between the devices and the temperature stress during epitaxy [1].

A second method uses two-step epitaxy to form the detector and the transistor, where the first layers are removed before the second epitaxy and the second epitaxial step is performed selectively. Using this method the two devices do not influence each other, but the device performance is limited by the regrowth and the associated interface quality. The regrown transistors suffer a degradation in the DC and RF performance. A 10 percent degradation of the transconductance and 50 percent worse cut-off frequency compared to discrete processed transistors have been found [2]. Nevertheless, a PIN-HEMT receiver with 18GHz bandwidth has been realized recently [3].

In the last time considerable attention is given to a third scheme, where both devices are prepared on an identical layer structure. This method has been only applied to PIN-HBT receivers, where the base-to-collector layer system is profited as photodetector. The integrated photoreceivers with the highest bandwidth and transmission rate are realized using this technology. Sensitivities of -10dBm and a deduced 23GHz bandwidth were achieved [4].

Another aspect is the planarity of the surface. A planar surface is absolutely necessary for high resolution lithography. To fulfill this requirement by one-step or two-step epitaxy the growth process must be initiated on substrates, which contain grooves of the appropriate depth, so that the complete circuit will be planar. For ease of fabrication, improved device performance and wafer yield it might be necessary to realize the integration with devices, which are based on an identical layer structure. However, MSM-PDs have higher ultimate speed than PIN devices [5], and HEMTs exhibit better high-frequency performance than HBTs. Moreover, we found that high-speed MSM-PDs can be prepared on two-dimensional electron gas (2DEG) structures [6-8].

In this paper we report on a novel monolithically integrated photoreceiver, which is usable for 10Gbit/s long-haul (1.3–1.55μm) optoelectronic transmission systems. Our monolithically integrated receiver consists of MSM-2DEG PDs and HEMTs, which are prepared on an identical InGaAs/InP heterostructure. Design considerations, preparation procedure and optoelectronic performance of discrete devices and front-end receiver circuits are presented.

II. PHOTORECEIVER DESIGN

Designing monolithically integrated photoreceivers we have considered that in general the use of MSM-PD-HEMT counterpart has the advantage of devices with a planar configuration. Therefore the manufacturability of these receiver circuits should be simpler and more cost effective.

Otherwise MSM-PDs exhibit a principally lower responsivity than PIN-PDs, but due to their higher speed the resulting bandwidth will be comparable to PIN-PDs [5]. Recently we proposed a novel MSM diode based on InP/InGaAs HEMT-like 2DEG structure. As we have shown this MSM-2DEG PDs offer high-speed detection (FWHM ≤ 60ps) at 1.3μm wavelength [6].

Furthermore it is known that InP-based HEMTs guarantee highest cutoff frequencies and lowest noise figures. On the other hand, Al-containing InP-based HEMTs show kink effects in their output (I-V) characteristics, lower breakdown voltages and shorter long-term stability, which can be attributed to the deep traps in InAlAs layers. Recently we reported on Al-free InP/InGaAs HEMTs with 0.2μm gate length and cut-off frequencies of f_T = 135GHz and f_{max} = 200GHz [9]. The obtained results are comparable to conventional InAlAs/InGaAs HEMTs.

Because of our results on discrete devices it should be possible to realize a photoreceiver by a simple preparation procedure using an identical InP/InGaAs 2DEG layer structure for the PD and the HEMT. In order to achieve sufficient responsivity of the MSM-2DEG PD, an absorption region of appropriate thickness should exist in the layer structure. For a good HEMT performance the distance between the Schottky barrier and the 2DEG should be as small as possible, mainly if sub-μm devices are used. Therefore a compromise is needed, i.e. an optimal thickness of InGaAs absorption layer must be found to obtain reasonable performance of both devices on an identical layer structure.

III. PREPARATION

Fig. 1 shows a cross-sectional schematic diagram of the Al-free layer structure grown by low pressure MOVPE on a semi-insulating InP substrate.

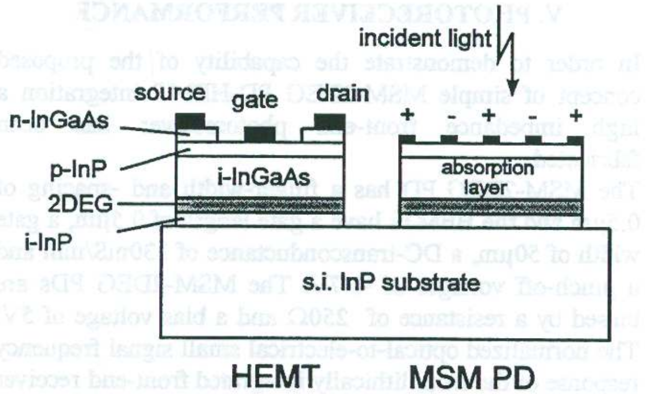

Fig. 1. Cross-sectional schematic diagram of the HEMT-MSM-2DEG PD layer structure.

The 2DEG is formed by an InP/InGaAs heterojunction, with the InP carrier supplying layer below the strained $In_{0.77}Ga_{0.23}As$ channel [10]. The 2DEG has a sheet carrier density of about $2.0*10^{12}cm^{-2}$ and an electron mobility of $12000cm^2/Vs$. A lattice-matched InGaAs layer above the 2DEG acts as absorption layer for incident infrared light. Structures with different thicknesses of the InGaAs absorption layer have been prepared. An p-doped InP layer is used to enhance the Schottky barrier on InGaAs. Finally a n-doped InGaAs cap layer is grown to optimize ohmic HEMT contacts.

Device fabrication consists of standard optical and electron-beam lithography, mesa insulation and metal evaporation processes. The ohmic and gate contacts of the HEMT are prepared by Ni/AuGe/Ni and Pt/Ti/Au metallization, respectively. HEMTs with different gate lengths between 1.1μm and 0.36μm have been prepared. The interdigitated contacts of the MSM-2DEG PD are carried out semitransparent (10nm Pt) to enhance the optical sensitive area. The finger-width and -spacing ranges between 0.5 and 3μm and the active area is $50*50μm^2$. No antireflection coating has been applied. The devices are insulatied by mesa etching and then Cr/Au contact pads are prepared for the probe measurements. MSM-2DEG PDs and HEMTs have been processed simultaneous on the same wafer.

IV. DISCRETE DEVICE PERFORMANCE

The direct current (DC) and high frequency (RF: 130MHz – 26.5GHz) properties of discrete MSM-2DEG PDs and HEMTs have been analyzed in order to study the influence of InGaAs absorption layer thickness on the device performance. Structures with InGaAs thickness d_a varying from 125nm to 500nm are investigated.

The electric field in a MSM-2DEG diode is mainly perpendicular to the surface due to the high-conductive 2DEG. Therefore the active device length is defined by the contact-2DEG distance in contrast to the conventional MSM structures, where the active length is only given by the distance between the contacts, i.e. by the finger spacing. The electrical-to-optical frequency response of MSM-2DEG PDs is measured on-wafer using an HP83420A light test set in combination with an HP8510B network analyzer. The devices are contacted by an ALESSI probe station. The light of 1.3μm wavelength is directed on the PD by a mono-mode glass fiber.

The typical measured frequency response of a MSM-2DEG PD (d_a = 150nm, 5V bias, 1.3μm wavelength) with 0.5μm finger-spacing and -width is shown in Fig. 2 and yields a 3dB bandwidth of 16 GHz.

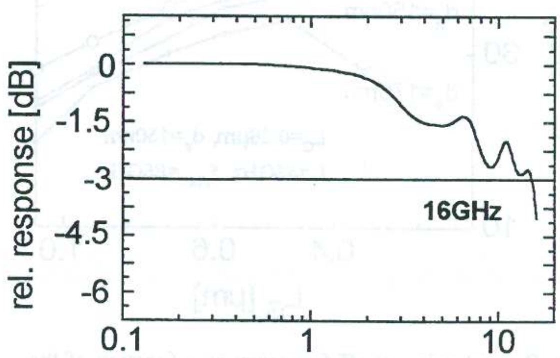

Fig. 2. Frequency response of MSM-2DEG photodetector (0.5 μm finger-spacing and -width, 5 V bias, 1.3 μm wavelength).

The time domain pulse response evaluated by Fourier transform exhibit a FWHM of 31 ps which is also the resolution limit of used measurement set. The MSM-2DEG PD has a front-side illumination responsivity of 0.21A/W for 1.3μm incident light and a dark current density less than $100pA/μm^2$. A low capacitance of 30fF at 5V applied bias is achieved, which is a good value for InGaAs based MSM PDs. The representative results of MSM-2DEG PDs with different absorption layer thicknesses are shown in Table I.

Table I. Bandwidth and responsivity of MSM-2DEG PDs with different InGaAs absorption layer thickness d_a.

d_a [nm]	3dB bandwidth [GHz]	responsivity [A/W]
125	16	0.15
150	16	0.21
175	12	0.27
250	8	0.36
500	6	0.64

InGaAs-based HEMTs with different gate lengths ranging from 1.1 µm down to 0.36 µm have been prepared on PD compatible InGaAs/InP structures with 125nm, 150nm and 175nm thick InGaAs absorption layer above the 2DEG. No kink effects in their I-V characteristics and relatively high breakdown voltages (≥ 7 V) have been observed. The transconductance has a value of 300-330mS/mm. Typical current gain cut-off frequencies, evaluated from S-parameter measurements, as a function of the gate length are shown in Fig. 3 (full dots). Cut-off frequencies obtained on RF-optimized InGaAs/InP HEMTs, i.e. on devices without an InGaAs absorption layer, are also displayed (open dots). The cut-off frequency f_T increases with decreasing gate-length L_G and saturates at gatelengths below 0.5µm. Also a decrease of f_T with increasing InGaAs thickness is observable.

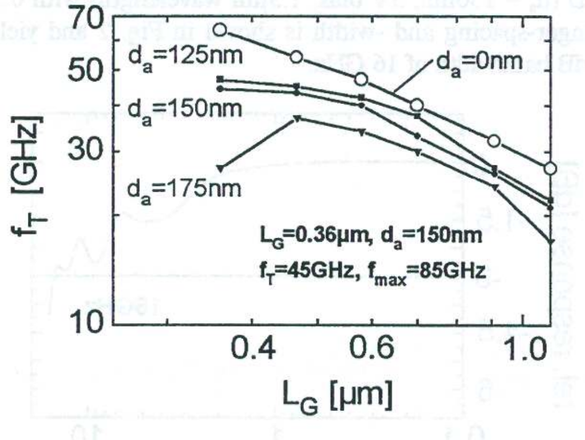

Fig. 3. Current gain cut-off frequency as a function of the gate length for PD-compatible and RF-optimized (d_a=0) InGaAs/InP HEMTs.

Both effects are explainable by short channel effects. For HEMT devices the gate-to-channel-aspect-ratio (gate-length/gate-to-channel-spacing) is important. If the ratio is less than 3, short channel effects occur leading to a source-drain voltage dependent drain current, an increasing output conductance and thereby to smaller cut-off frequencies. Therefore the thickness of the InGaAs absorption layer is the most critical parameter for HEMTs, which are based on the MSM-2DEG PD layer structure [7]. A large InGaAs sensitive layer leads to a high detector responsivity, but also results in a small gate-to-channel aspect ratio, in a poor gate control and RF performance. The thickness of the sensitive layer must be chosen as a compromise between detector responsivity and HEMT performance and should fulfill the requirements of both devices. Thus the integrated transistors are not expected to have record values and exhibit 20 percent lower cut-off frequencies as high frequency optimized HEMTs with small gate-to-channel distances of 30nm. Nevertheless, cut-off frequencies of f_T = 45GHz and f_{max} = 85GHz have been measured on PD-compatible HEMTs with 150nm InGaAs absorption layer thickness and 0.36µm gate length. These results lead to the conclusion [6-8] that:

i) MSM-2DEG PDs are especially suitable for the preparation of low capacitance, broad-banding and high-speed photodetectors.

ii) A good performance of MSM-2DEG PDs and HEMTs can be achieved if they are prepared on an optimized layer structure, which is identical for both types of discrete devices.

iii) The monolithically integration of these devices into a photoreceiver with technological and cost advantages is possible.

V. PHOTORECEIVER PERFORMANCE

In order to demonstrate the capability of the proposed concept of simple MSM-2DEG PD-HEMT integration a high impedance front-end photoreceiver has been fabricated.

The MSM-2DEG PD has a finger-width and -spacing of 0.5µm and the HEMTs have a gate length of 0.5µm, a gate width of 50µm, a DC-transconductance of 330mS/mm and a pinch-off voltages of -1.7V. The MSM-2DEG PDs are biased by a resistance of 250Ω and a bias voltage of 5V. The normalized optical-to-electrical small signal frequency response of the monolithically integrated front-end receiver is shown in Fig. 4. The receiver has a 3dB bandwidth of 2.1GHz and an amplification of 17dB on 50Ω compared to a single MSM-2DEG PD. The bandwidth of the front-end receiver can be improved by optimizing the receiver

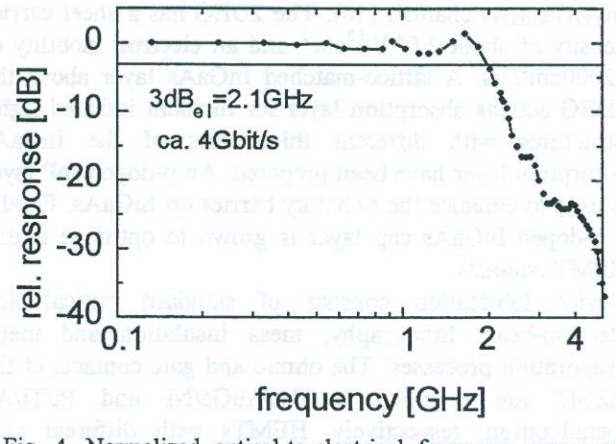

Fig. 4. Normalized optical-to-electrical frequency response measured on the monolithically integrated MSM-2DEG PD-HEMT front-end receiver.

circuit, for example by inserting inductances between the HEMT and the MSM-2DEG PD (see Fig. 6). The inductances form a high frequency resonance resulting in an extended bandwidth [11, 12], without affecting the gain. To investigate the influence of this technique ("inductive peaking") the frequency response of the receiver has been calculated. Therefore the S-Parameters of both devices are measured first. Using this data equivalent

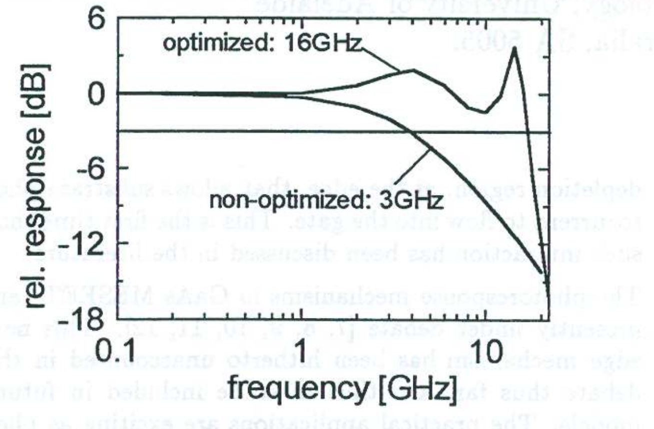

Fig. 5. Frequency response of a monolithically integrated MSM-2DEG PD-HEMT photoreceiver for non-optimized and optimized front-end receiver circuit.

circuit modeling by a SPICE program yields the frequency response and also the optimal values for the passive elements, especially the inductances. The obtained results concerning the non-optimized (described before), as well as the optimized (inductive tuned) monolithically integrated receiver version are shown in Fig. 5. The achieved 3dB bandwidth of 3GHz of the non-optimized circuit is in good agreement with the measured value of 2.1GHz. The inductive tuned receiver yields a 16GHz bandwidth, which is comparable to the record bandwidth of 18GHz recently reported on an InGaAs-based pin/HEMT receiver [3]. But in this case complicated preparation consisting of two-step epitaxy is used (first HEMT is grown by MBE and then PIN-PD by CBE).

The gain of our receiver can be improved for example by a common-gate-source-follower amplification stage after the inductive tuned front-end stage (Fig. 6). Simulations show that a gain of 30dB and a bandwidth of about 7GHz are possible, useful for 10Gbit/s transmission rates.

A further improvement of the gain and bandwidth is possible by using a transimpedance amplifier.

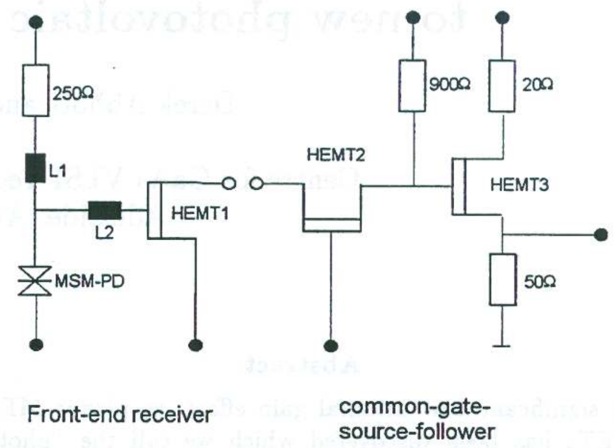

Fig. 6 Schematic circuit layout of front-end receiver circuit with optional inductances (L1=9nH, L2=4nH) for bandwidth enhancement ("optimized") and common-gate-source-follower as second amplification stage

VI. CONCLUSION

A novel type of monolithically integrated photoreceiver for 10 Gbit/s long-wavelength (1.3µm) optoelectronic transmission systems has been developed. The photoreceiver consists of an MSM-2DEG photodetector and a HEMT amplifier. Both devices are prepared on an identical InGaAs/InP 2DEG layer structure. This procedure allows the realization of monolithically integrated photoreceivers with high performance, simple preparation procedure and low-cost manufacturability.

Concerning the photoreceiver preparation, an optimal InGaAs/InP 2DEG layer structure has been found, demonstrated on the performance of discrete devices. The MSM-2DEG photodetectors exhibit a 3dB bandwidth of 16GHz. The HEMT amplifiers with 0.36µm gate length have the cut-off frequencies f_T = 45GHz and f_{max} = 85GHz. On the base of these results monolithically integrated front-end receivers have been fabricated. A 2.1GHz bandwidth on front-end receiver circuit is measured and a bandwidth of 16GHz on optimized circuits can be achieved. Therefore the use of these devices in 10Gbit/s optoelectronic transmission systems is possible.

REFERENCES

[1] K. Pedrotti, Proc. of the SPIE, Vol. 2149, p.178, (1994).

[2] D.T.Nichols, N.K.Dutta, P.R.Berger, P.R.Smith, D.Sivco, and A.Y.Cho, Proc. of the SPIE, Vol. 2149, p.414, (1994).

[3] B.-U.H.Klepser, J.Spicher, M.Beck, C.Bergamaschi, W.Patrick, W.Bächtold, Electron. Lett. 31, p.1831 (1995).

[4] E.Sano, M.Yoneyama, S.Yamahata, Y.Matsuoka, Electron. Lett. 30, 2064 (1994).

[5] M.Horstmann, M.Marso, P.Kordoš, "MSM-PDs based on InP/InGaAs 2DEG structures", in Strained-layer quantum-wells and their applications, Ed. by M.O. Manasreh, Gordon and Breach (in press).

[6] M. Horstmann, M. Marso, A. Fox, F. Rüders, M. Hollfelder, H. Hardtdegen, P. Kordoš, H. Lüth, Appl. Phys. Lett. 67, p.106 (1995).

[7] M. Horstmann, M. Marso, K. Schimpf, F. Rüders, A. van der Hart, M. Hollfelder, H. Hardtdegen, P. Kordoš, H. Lüth, Proc. 25th ESSDERC, p. 443 (1995).

[8] M.Horstmann, K.Schimpf, M.Marso and P. Kordoš, Electron. Lett. in press (1996).

[9] K.Schimpf, M.Hollfelder, M.Horstmann, M.Marso, H.Hardtdegen and P.Kordos, Proc. 8th IPRM, Schwäbisch Gmünd, Germany, in press (1996).

[10] R.Meyer, H.Hardtdegen, A.Leuther, M.Marso, P.Kordoš, H.Lüth, Proc. 5th IPRM, Paris, France, p. 485, (1993).

[11] T. Mallikarjun, Proc. of the SPIE, Vol. 2149, p.397, (1994).

[12] D.Kuhl, E.H.Böttcher, F.Hieronymi, E.Dröge, and D.Bimberg, Photonics Tech. Lett. 7, p. 421, (1995)