Performance Improvement of a Monolithically Integrated C-Band Receiver Enabled by an Advanced Photonic BiCMOS Process

S. Lischke, D. Knoll, M. H. Eissa, M. Kroh,
A. Peczek, and L. Zimmermann
IHP, Im Technologiepark 25,
15236 Frankfurt (Oder), Germany
lischke@ihp-microelectronics.com

A. Awny
now with Inphi GmbH, Walsroder Str. 93/93a,
30853 Langenhagen, Germany

***Abstract*—A monolithically integrated C-band receiver is used to demonstrate the potential of an advanced photonic BiCMOS process. We show that the particular SiGe HBTs integrated in this process strongly improve the receiver's frequency response, BER and noise behavior, compared to the same circuit fabricated in a previous process generation featuring slower transistors.**

Keywords—BiCMOS; SiGe; Silicon Photonics

I. Introduction

Recently, silicon-based, monolithically integrated direct receivers for data rates up to 40 and 56 Gbps, respectively, were demonstrated for the first time [1–3]. These circuits were fabricated in IHP's photonic SiGe BiCMOS process SG25H4_ePIC, an electronic photonic integrated circuit (ePIC) technology featuring SiGe heterojunction bipolar transistors (HBT) with f_T/f_{max} of 170/200 GHz and Ge photodiodes with up to 70 GHz optical-electrical bandwidth and C-band responsivity of about 1 A/W. More process and device details of this technology can be found elsewhere [4, 5].

However, the realization of next generation communication systems with optical line rates of 100 Gbps and beyond requires, on the receiver side, higher transistor RF performance for trans-impedance amplifier (TIA) designs than it is typically offered by existing Si-based ePIC technologies. To overcome this bottleneck, an advanced photonic BiCMOS process was recently introduced, providing SiGe HBTs with f_T/f_{max} values of up to 240/290 GHz, i.e. about 40% higher transistor RF performance compared to the first process generation [6].

In this paper we demonstrate for the first time an integrated receiver fabricated in the new process. To assess the particular gain in receiver performance which results solely from replacing the original bipolar transistors by faster ones, we used a receiver design which was already proven to be fully functional with fabrication in the "old" process [3]. Switching from previous to the advanced process was eased by the fact that the higher HBT RF performance of the new process results only from changes in the HBT module process flow but doesn't need any changes in the transistor design.

Our primary results can be summarized as follows: (1) A Si-based, monolithically integrated C-band direct receiver was fabricated showing -3 dB bandwidth of more than 50 GHz. Moreover, the receiver -1 dB bandwidth was improved by about 40 % compared to a receiver with identical design but fabricated in a process which provides slower transistors. (2) For reception of 40 Gbps data stream, the optical input power for < 10^{-10} bit error rate (BER) was reduced by more than a factor of 2 by the use of faster HBTs. (3) Receiver with new transistors also shows about 20% lower input equivalent noise.

The paper is organized as follows. First, we briefly describe the advanced process. Then, receiver measurement results are presented and discussed, followed by a concluding summary.

II. Advanced Photonic BiCMOS Process

Fig. 1 illustrates the integration of photonic modules in the BiCMOS baseline technology, using an integration scheme as described in [4].

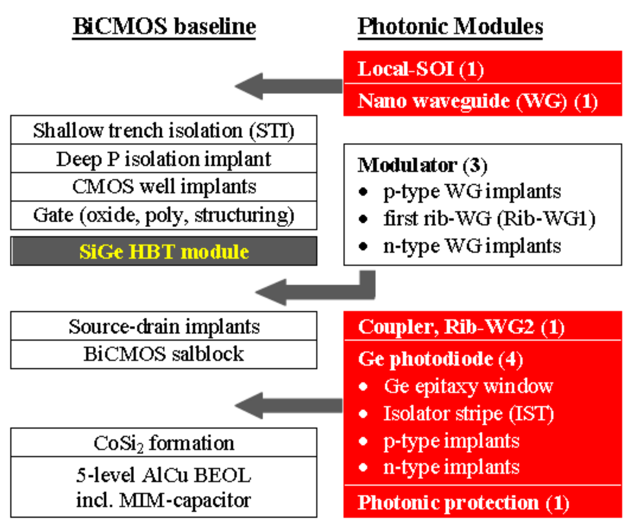

Fig. 1: Photonic BiCMOS process flow: Photonic modules are integrated in a SiGe BiCMOS process. The process starts with an SOI-substrate with optimum dimensions for photonic application: 220 nm silicon on 2 µm buried silicon oxide (BOX). The local-SOI approach realized with the first photonic module allows one to combine SOI-based photonic components with a bulk BiCMOS core. Red marked modules are needed to fabricate a waveguide-coupled Ge p-i-n photodiode. Numbers in brackets indicate the additional mask steps over the 26-mask BiCMOS core.

The improvement in the SiGe HBT RF performance, compared to [4], was reached by adapting the HBT module of IHP's BiCMOS process SG13S [7] to the ePIC process. Details of the advanced photonic BiCMOS process have already been presented elsewhere [6].

Cross-sections of the old and the new SiGe HBTs are shown in Fig. 2. Better RF performance of the new transistors results from:

- Scaling the vertical profile to increase f_T: emitter-base and base-collector junction widths were reduced, base Ge content increased, and base boron doping lowered.
- Introduction of an elevated external base to reduce the external base resistance (R_{BX}, see Fig. 2, below) as key measure for a strong gain in f_{max}: total base resistance is nearly maintained by this new transistor structure feature despite an increase of internal base resistance due to the lowered base boron doping.

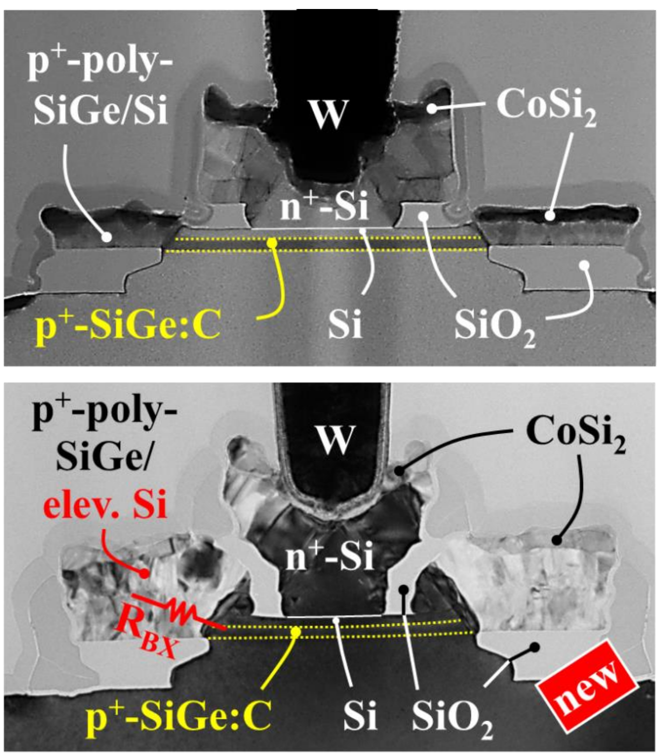

Fig. 2: TEM cross-sections of the old (top) and new SiGe HBTs (bottom). The major change is the elevated external base leading to a reduction of the external base resistance (R_{BX}), being beneficial to f_{max}.

III. Receiver Results

The receiver consists of a waveguide-coupled germanium photodiode monolithically integrated with a trans-impedance amplifier and low frequency feed-back loop to compensate for the DC input overload current. Bandwidth enhancement techniques are used to extend the bandwidth compared to previously published monolithically integrated receivers. Light can be coupled to the waveguide by use of a 1D grating coupler optimized for 1.55 µm wavelength. A detailed description of the receiver including the block diagram, circuit schematics and comprehensive characterization is available elsewhere [3].

Next, only the implications due to improved HBT RF performance are presented and discussed. Fig. 3 shows O-E response vs. frequency for receivers fabricated in the "old" or the advanced process. Obviously, the faster HBTs improve considerably the response behavior, in particular in the frequency range between 20 and 50 GHz, at a rather weak gain in -3 dB bandwidth of about 5 GHz. However, the receivers with faster HBTs provide a bandwidth of more than 50 GHz.

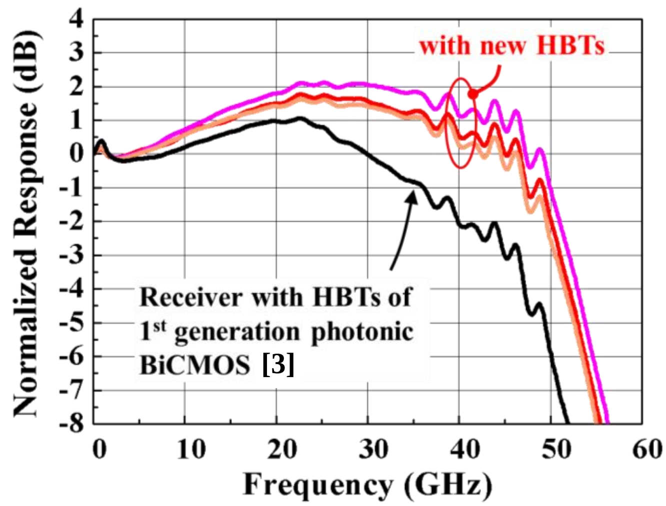

Fig. 3: Normalized O-E frequency response of monolithically integrated photonic direct receivers with identical design, fabricated in IHP's first generation photonic BiCMOS process or in an advanced process version featuring faster SiGe HBTs (three chips of one wafer were measured for this case). Measurements were carried out at λ = 1.55 µm.

Receiver group delay behavior is compared in Fig. 4. Delay variation is about $\pm$10 psec till 50 GHz for the circuit fabricated in the advanced process. So it is higher than that of the receiver with slower HBTs, naturally because the peaking is higher. It is, however, still okay as can be seen from the 40 Gbps eye-diagram (Fig. 5) which does not exhibit strong overshoots.

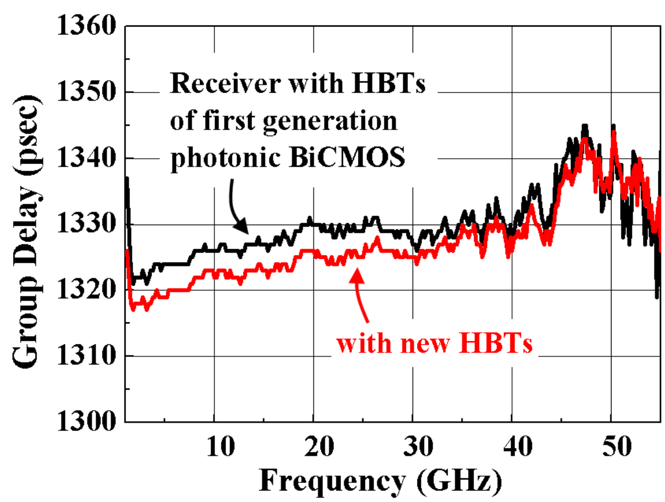

Fig. 4: Group delay vs. frequency of monolithically integrated photonic receivers with same design, fabricated in IHP's first generation photonic BiCMOS process or in an advanced process version featuring faster SiGe HBTs.

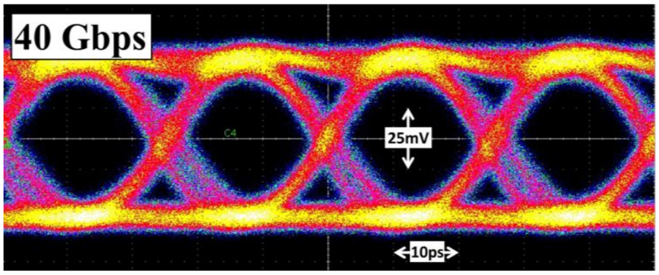

Fig. 5: Eye-diagram at 40 Gbps (2^{31}-1 PRBS) of a monolithically integrated direct receiver fabricated in the advanced photonic BiCMOS process. PD current: 260 µA.

From the improved frequency response behavior one could also expect better BER characteristics of the receivers fabricated in the advanced process, as it is actually proven by Fig. 6. Bit error rates are shown there as a function of the photo current to exclude implications by differences in the grating coupler losses or the detector responsivities.

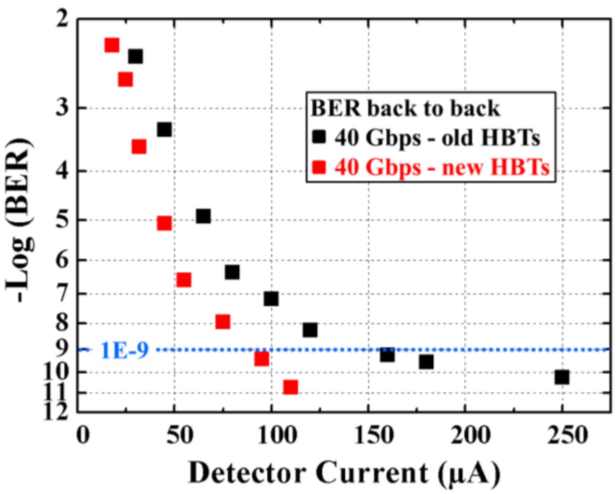

Fig. 6: BER vs. PD current for 40 Gbps: Comparison of monolithically integrated receivers with new and old HBTs.

Obviously, the use of faster HBT lowers the current for minimum bit error rate by a factor of more than 2 for reception of 40 Gbps data stream.

Considering the actual grating coupler behavior, featuring about 4.5 dB loss at λ = 1.55 µm for the "old" and 4.25 dB in the "advanced" case, and detector responsivities of 0.7 A/W and 0.9 A/W at this wavelength for "old" and "advanced" receiver, respectively, measured on test structures located in close proximity to the circuits, the improvement of the "opto-electronics" by use of faster HBTs for the trans-impedance amplifier leads also to a strong reduction of optical input power for a given BER, as shown in Fig. 7. One can see that for reception of 40 Gbps data stream, the power for < 10^{-10} BER was reduced by more than a factor of two by the use of faster SiGe HBTs.

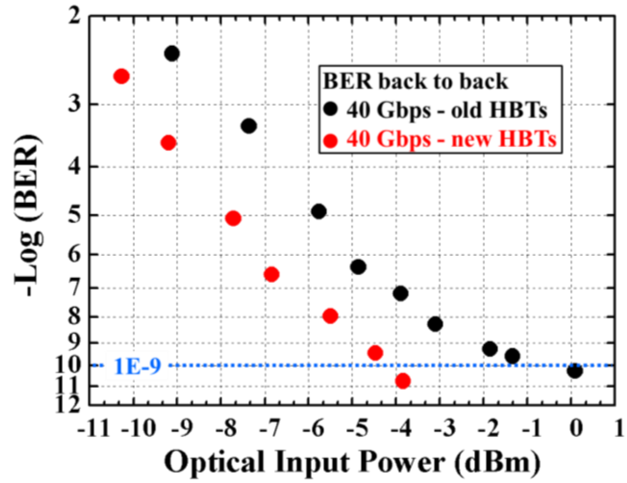

Fig. 7: BER vs. optical input power for 40 Gbps: Comparison of monolithically integrated receivers with new and old HBTs.

Table 1 compares Si-based, state-of-the-art monolithically integrated receivers with the results of this work demonstrating superiority of the new circuit, when fabricated in the advanced photonic BiCMOS process, for some key parameters, such as bandwidth and sensitivity. Moreover, the noise behavior is also considerably improved, by about 20 %, by use of faster transistors for the TIA.

IV. Conclusions

We demonstrated strong performance improvements of a monolithically integrated wideband receiver by equipping the

TABLE 1: BENCHMARK OF SI-BASED, STATE-OF-THE-ART, MONOLITHICALLY INTEGRATED PHOTONIC RECEIVERS

Reference	[8]	[9]	[4]	[1]	[2]	[3]	**This Work**
Technology	90nm CMOS	130nm CMOS	0.25 um SiGe BiCMOS ("old" HBT)				("new" HBT)
Bandwidth (GHz)	-	25	14	31	36	47	**> 50**
Data Rate (Gbps)	28	25	25	40	56	40/54	40
Transimpedance (dBΩ)	-	67	71	65	66	49	49
Power (mW)	-	48	57	275	-	73	73
Sensitivity (dBm)	-2.7	-6	-15	-3	-	0.2/0.97	**-3.8**
BER	10^{-11}	10^{-11}	10^{-2}	2.5×10^{-11}	2×10^{-7}	$4.5 \times 10^{-11}/1.05 \times 10^{-6}$	**1.9×10^{-11}**
Input equivalent noise (pA/sqrt(Hz))	-	40	18	28.1	-	16.3	**13.1**
Efficiency (pJ/bit)	-	1.9	2.3	6.9	-	1.35	1.35
PD responsivity (A/W)	0.6	0.8	0.6	0.8	0.84	0.7	0.9
PD bandwidth (GHz)	15	17.6	35	31	>40	70	70
Power supply (V)	-	1.2	-	3.3/3.7	-	2.1/3.1	2.1

transimpedance amplifier with the faster transistors of an advanced photonic BiCMOS process. Compared to the receiver fabricated in IHP's first generation photonic BiCMOS process [3], BER and sensitivity at 40 Gbps were significantly improved. The results of this work indicate the potential of this novel technology and pave the way for the fabrication of receiver ICs for data rates towards 100 Gbps or beyond.

Acknowledgment

The authors gratefully acknowledge support by German Ministry of Research and Education (BMBF), project SPEED, as well as support by European Commission projects SITOGA, BEACON, PHRESCO, and DIMENSION.

References

[1] A. Awny *et al.*, "A 40 Gb/s Monolithically Integrated Linear Photonic Receiver in a 0.25µm BiCMOS SiGe:C Technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 7, pp. 469–471, 2015.

[2] M. Kroh *et al.*, "Monolithic Photonic-Electronic Linear Direct Detection Receiver for 56Gbps OOK," in *2016 European Conference on Optical Communication (ECOC)*, pp. 1157–1159.

[3] M. H. Eissa *et al.*, "A wideband monolithically integrated photonic receiver in 0.25-µm SiGe:C BiCMOS technology," in *IEEE European Solid State Circuits Symposium*, pp. 487–490, 2016.

[4] D. Knoll *et al.*, "Monolithically Integrated 25Gbit/sec Receiver for 1.55µm in Photonic BiCMOS Technology," in *Optical Fiber Communication Conference (OFC)*, 2014, p. Th4C.4.

[5] S. Lischke *et al.*, "High bandwidth, high responsivity waveguide-coupled germanium p-i-n photodiode," *Optics express*, vol. 23, no. 21, pp. 27213–27220, 2015.

[6] D. Knoll *et al.*, "High-Performance Photonic BiCMOS Process for the Fabrication of High-Bandwidth Electronic-Photonic Integrated Circuits," in *2015 IEEE International Electron Devices Meeting (IEDM)*, 2015, pp. 402–405.

[7] H. Rucker *et al.*, "A 0.13µm SiGe BiCMOS technology featuring f_T/f_{max} of 240/330 GHz and gate delays below 3 ps," in *2009 IEEE Bipolar/BiCMOS Circuits and Technology Meeting - BCTM*, 2009, pp. 166–169.

[8] S. Assefa *et al.*, "Monolithically Integrated Silicon Nanophotonics Receiver in 90nm CMOS Technology Node," in *Optical Fiber Communication Conference*, 2013, p. OM2H.4.

[9] J. F. Buckwalter, X. Zheng, G. Li, K. Raj, and A. V. Krishnamoorthy, "A Monolithic 25-Gb/s Transceiver With Photonic Ring Modulators and Ge Detectors in a 130-nm CMOS SOI Process," *IEEE J. Solid-State Circuits*, vol. 47, no. 6, pp. 1309–1322, 2012.