State and Applications of Si/SiGe High Frequency and Optoelectronic Devices

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The turnover of microelectronic devices and circuits has been rapidly growing from \$ 45 billion in 1990 to \$ 77 billion in 1993 to about \$ 350 billion in the year 2000. Since silicon (Si) is the overwhelmingly dominating material in this market with an over 97% share there has been a great incentive to develop the silicon/germanium (SiGe) heterodevices due to their superior performance compared to conventional Si devices and due to their full compatibility with the widespread and mature Si technology. Accessible market shares will depend on cost/performance advantages, therefore SiGe heterobipolar transistors (HBT's), SiGe hetero-field effect transistors (HFET's), and SiGe hetero CMOS (HCMOS) circuits are very competitive devices which fit best into the respective Si markets. We report here about performance of SiGe HBT's, MODFET's and IR detectors, about relevant circuit applications, and in the last section we give some forecasts for SiGe in the RF market.

1. Introduction

The strong research activities worldwide in the recent past in growing and processing reproducibly and commercially silicon/silicon-germanium (Si/SiGe) heterostructures (even on an atomic scale) has turned out Si based devices which can be grown by MBE, LPCVD, or UHVCVD. The performance of these devices, such as the SiGe base heterobipolar transistor (HBT) and the SiGe modulation doped field effect transistor (MODFET) or HEMT (high electron mobility transistor), is superior compared to their Si based counterparts, which substantially broadens the performance and functionality spectrum of Si microelectronics.

The potential of SiGe heterostructure devices has already been demonstrated by many University groups and companies, such as DaimlerChrysler, GEC, Hitachi, Intel, NEC, Siemens, TEMIC, SGS Thompson. Today the chip manufacturers come into play and also system partners are included. The focus of activities has now shifted from single devices to circuits. In this paper we describe briefly the basic principles of opto- and microelectronic SiGe heterostructure devices and circuit applications, finally we give a short overview on the expectations for SiGe microelectronic devices in the RF market.

2. SiGe Microelectronic Devices

Silicon based HBT's are npn bipolar transistors with a thin (<50 nm) pseudomorphically grown $Si_{1-x}Ge_x$ alloy layer as the base. High Ge contents up to 50% can be incorporated, and compared to standard Si BJT's (bipolar junction transistors), the base may be as thin as 5 to 10 nm, which helps to decrease the base transit time and raises the cutoff frequency of the transistor. In addition, the doping in the base may be extremely

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high, above 10^{20} cm^{-3}, which reduces the base sheet resistance. The highest maximum oscillation frequency f_{max} from an HBT has been achieved with a base sheet resistance below 1 kΩ/ .

The DC performance of a SiGe HBT is basically governed by the high current gain due to suppressed hole re-injection because of emitter-base valence band offset [1]. This is elucidated by the Gummel plot in Fig. 1 showing the current gain as a function of emitter-base voltage from a passivated SiGe HBT coming out from a production line.

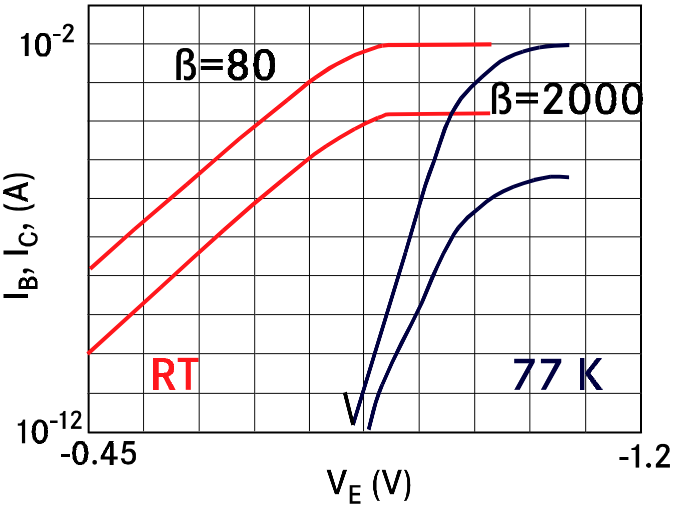
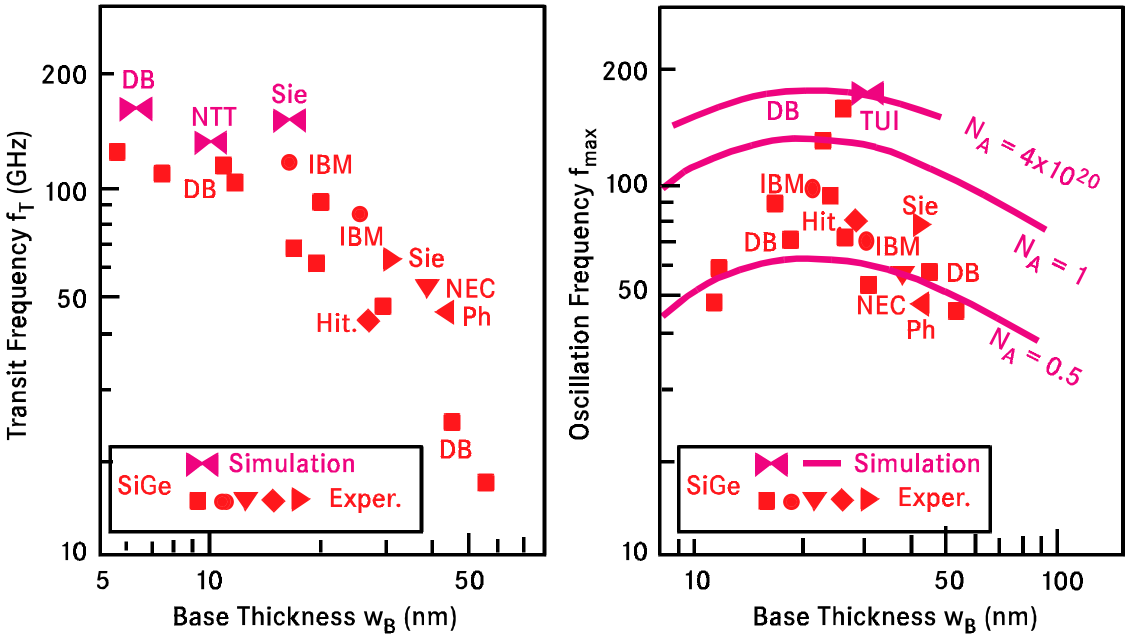


Fig. 1: Gummel plots of SiGe HBT’s at room temperature and 77 K from a passivated SiGe HBT from a Si production line (TEMIC).



(a) (b)

Fig. 2: Transit frequencies (a) and maximum oscillation frequencies (b) of SiGe HBT’s, measured by various labs ($N_A = 0.5x10^{20}$ cm^{-3} resp. $4x10^{20}$ cm^{-3}).

Nearly constant current gains over 9 decades are observed with a high gain value β of 2000 at 77 K (80 at RT). The application potential for “high β” HBT’s for low noise amplifiers in the lower GHz range which can further raise the dynamic input resistance is presently not exploited. The high frequency properties of various SiGe HBT’s are summarized in the transit and maximum oscillation frequency (f_t and f_{max}) plot versus base thickness for various companies (DaimlerBenz, Hitachi, NEC, Siemens, Philips, TEMIC) shown in Fig. 2 [2] – [4]. Record values of f_t of 116 GHz and f_{max} of 160 GHz have been achieved by the DaimlerChrysler Research group with base thicknesses of 7 and 37 nm. The maximum transit frequencies at lower base width result also in lower f_{max} values due to the distinctly higher base resistance. The f_t/f_{max} ratio depends strongly on the collector design. A thin, heavily doped collector favors higher f_t values. Today HBT’s with equal f_t and f_{max} of about 70 – 80 GHz can be fabricated. The frequencies increase with collector current up to a rapid fall off attributed to the Kirk effect which can be also seen for passivated devices [5], [6]. By increasing the collector/emitter voltage V_{CE} f_{max} can be furthermore increased due to reduction of the collector/base capacitance [5].

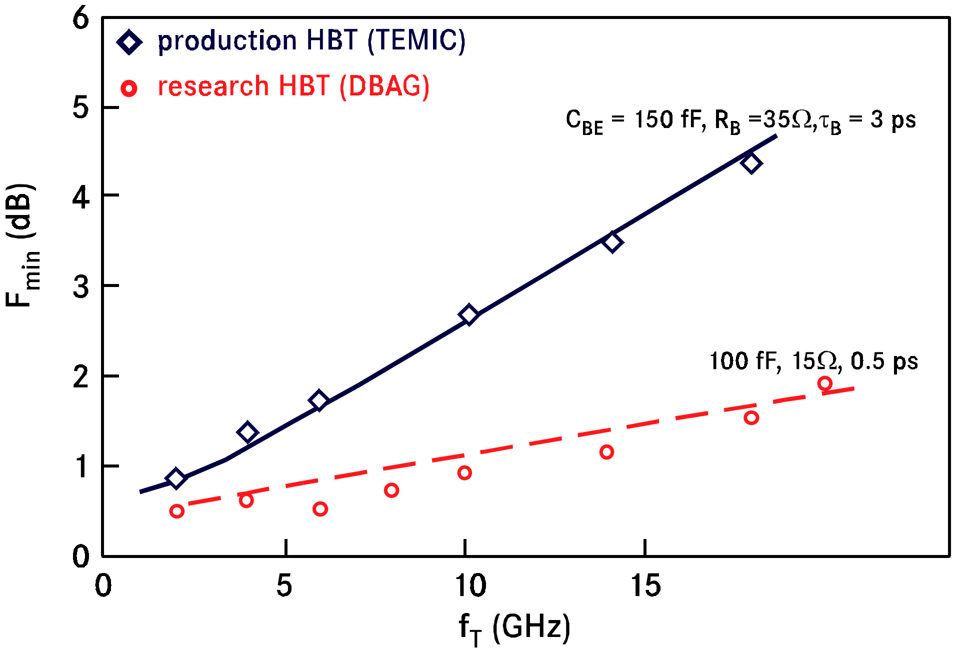


Fig. 3: High frequency noise of mesa chip HBT’s and packaged HBT’s. Simulated influence of base-emitter capacitance, base resistance and base transit time.

Another figure of merit is the high and low frequency noise. Fig. 3 compares the noise figure F_{min} for frequencies above 2 GHz for research HBT’s and for marketable packaged HBT’s (in SOT 343 or 143) [7], [8]. The noise figure from a production line HBT is still below 1 dB at 10 GHz which can be seen in Fig. 3 which compares the noise figures of a research mesa HBT with a planar passivated production HBT. The corner frequency f_C, which marks the transition point from 1/f noise to the shot noise is below 300 Hz, even for packaged HBT’s [8], [9]. The Gummel plot gives an idea of the size of f_C as shown in Fig. 4. Parallel collector and base currents guarantee low corner frequencies below 1 kHz.

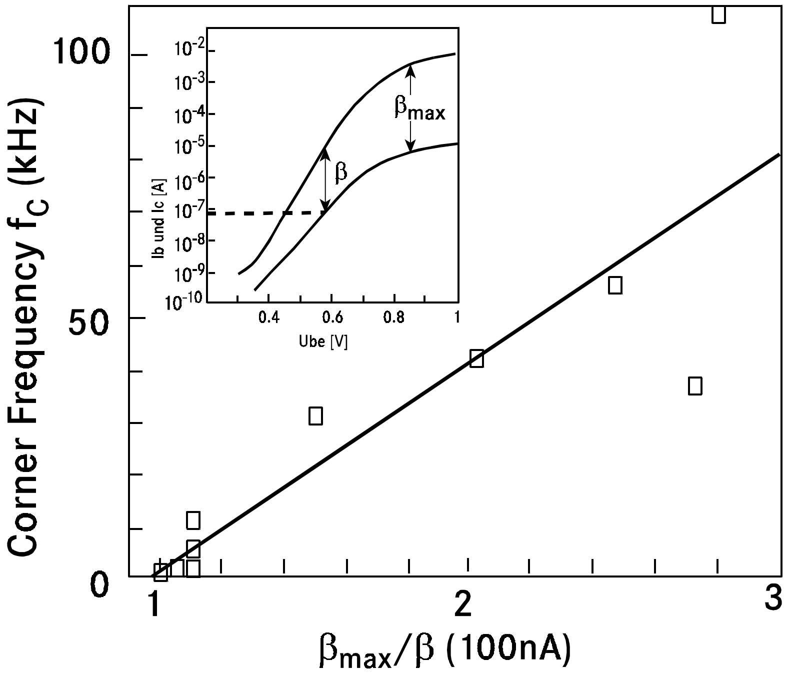


Fig. 4: Corner frequency related to the non-ideality of the Gummel plot (ratio of gain at high and low currents).

Si/SiGe power HBT's intended for 1.9 GHz applications either using 60 emitter fingers exhibited a collector/emitter breakdown voltage of 4.5 V with f_T and f_{max} values of 16 and 11 GHz, respectively, at a collector current of 400 mA. Class A power added efficiencies (PAE) of 44% at 1 W output power and PAE's of 72% at 900 MHz for class A/B operation have been measured. These data are achieved without any thermal shunt precautions in the contacts and without substrate thinning, which reflects the benefits of a Si substrate.

3. Si/SiGe HFET's

The band alignment of the Si/SiGe heterostructure favors the creation of carrier channels by modulation doping (carriers separated from dopant atoms). In a SiGe MODFET high carrier mobilities of 2900 cm^2/Vs and 1800 cm^2/Vs result for the two-dimensional electron or hole gas respectively [10], [11] and sheet carrier concentrations up to $2.5x10^{12}$ cm^{-2}. This also holds true in the case of a hetero MOSFET when the channel is buried under the gate and the interface scattering is strongly reduced due to the more perfect Si/SiGe interface. In addition, an increased velocity overshoot has been predicted due to the strain in the channels [12].

Figure 5 compares the DC performance of good n-HFET's, all of them with Schottky gates. The operation mode – depletion or enhancement – can be chosen by adjusting the doping in the supply layers above or below or even within the channel and by the layer thickness, e.g. cap layers above the channel. A gate recess, for example, can switch enhancement mode to depletion mode. Record values for extrinsic transconductances in depletion HFET's from 290 to 310 mS/mm at RT have been measured for depletion n-HFET's and 480 to 510 mS/mm for enhancement FET's at RT and up to 780 mS/mm at 77 K. Transconductances of p-HFET's are usually smaller (e.g. around 250 mS/mm for 0.2 – 0.25 µm gate length). However, theory predicts values similar to n-HFET's when using a Ge channel in the p-HFET [12]. High currents of 320 and 200 mA/mm have been obtained for depletion or enhancement mode n-HFET's and currents up to 600 mA/mm have been obtained for MOS gated p-HFET's (3,7 nm SiO_2).

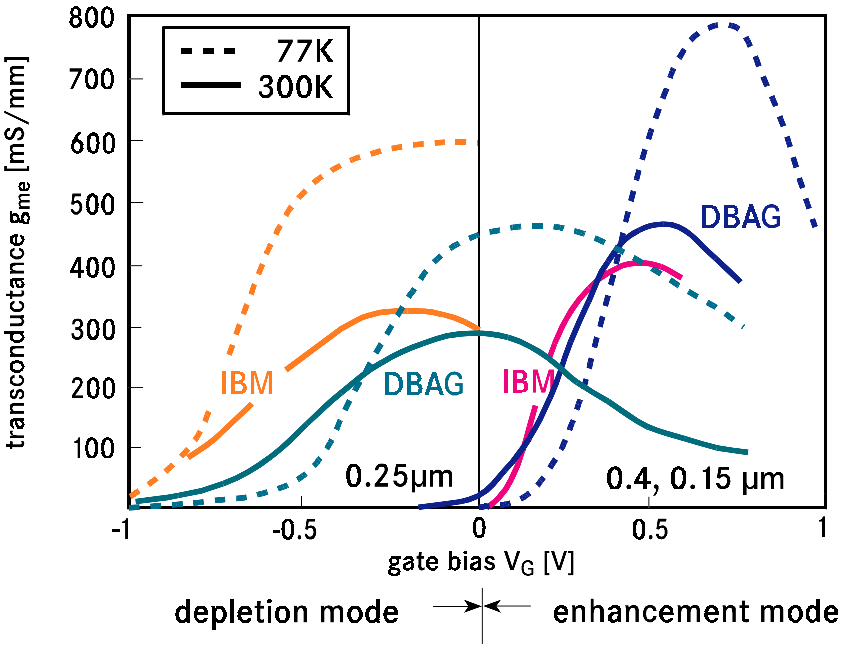


Fig. 5: Transconductances at room temperature and 77K of depletion and enhancement mode SiGe HFET's.

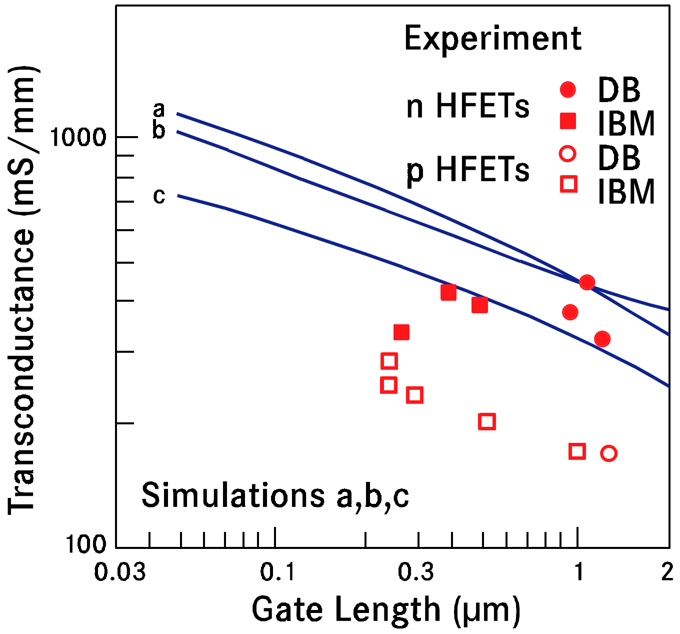
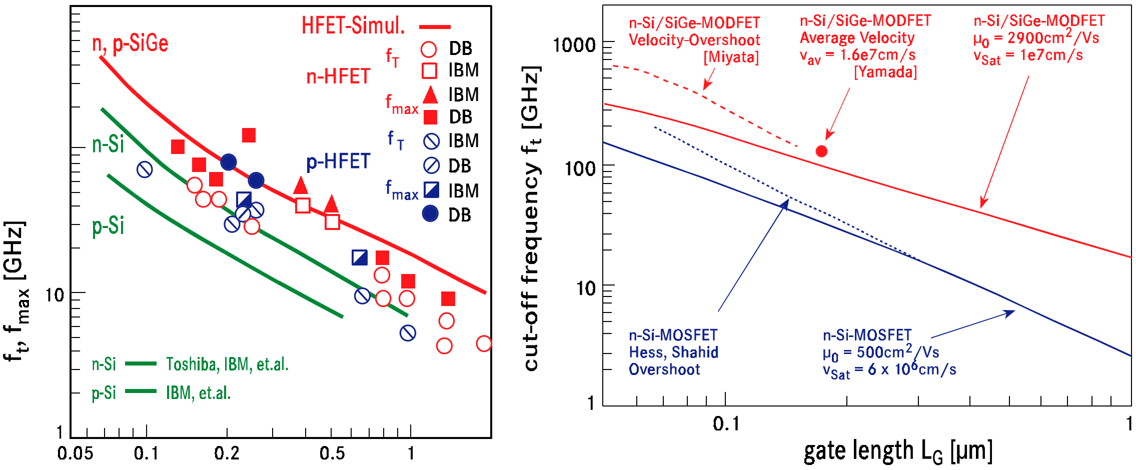


Fig. 6: Gate length dependence of the transconductance of n-HFET's. Experimental data reported compared to simulations.

Figure 6 makes a comparison of the transconductance status with expectations. Experiments have not established the significant gate length dependence (a, b, c) expected from theory [12]. Cut off frequencies f_{max} of 78 to 92 GHz and f_T of 43 to 46 GHz had been extrapolated from the gain curves. The lower drain source voltage V_{DS} of the order of 1V for voltage independent operation underlines the low power potential in digital circuits of SiGe HFET's.



(a) (b)

Fig. 7: Gate length dependence, (a) measurements of n- and p-type HFET's and (b) simulations for n-SiGe HFET's with and without velocity overshoot [15].

In Fig. 7, most of the frequencies f_T and f_{max} achieved so far for n- and p-HFET's are plotted versus gate length [13], [14] from IBM and our group. The gate length dependence of the cutoff frequencies are clearly visible, simulation predicts maximum cutoff frequencies of up to 200 GHz for gate length below 0.1 μm or even higher (>400 GHz) if velocity overshoot really exists [12], [15]. On the other hand, HFET devices with a relaxed gate layout of 0.35 to 0.8 μm have a better performance than Si MOSFET's and benefit from the manufacturability in a standard Si MOS production line.

4. Circuit Applications Using SiGe HBT's and HFET's

Presently the HBT is the best developed SiGe device, and it is an ambitious and time consuming goal to implement such a new technology into the well established Si production line of a chip manufacturer. By now those circuits are commercially available (*PA U7004B* from TEMIC) but so far mainly for special system customers with whom the chip manufacturer cooperates.

Various HBT circuits have been reported so far with promising performances. Figure 8 shows a chip with circuits for 5 to 40 GHz operation realized on semi-insulating substrate. A 12 bit digital to analog converter operating at 1 GHz has been demonstrated by IBM together with ADI [16]. NEC has reported an D-type flip-flop for 20 Gbit/s, a selector for 30 Gbit/s and 33ps, a 2:1 multiplexer for 20 Gbit/s and preamplifier with 19 GHz and 36 dbΩ [17]. Furthermore a multiplexer and a demultiplexer with 28 Gbit/sec have been realized by the Ruhr University Bochum using our samples. A wideband amplifier capable of 9.5 dB gain with 18 GHz bandwidth and a power consumption of 50 mW from a 3 V supply which operates at 1.6 V has been realized [18]. Varactor controlled oscillators with Si/SiGe HBT's for different frequency ranges from 1.8 up to 40 GHz were presented by Nortel together with IBM, by TEMIC, and by IBM [19], [20]. Power amplifiers for 0.9 up to 2 GHz have been realized by TEMIC together with our group (DCAG) [21] and by Philips; LNA's with an F_{min} of 1.7 to 1.9 dB have been presented by TEMIC (with DCAG and University of Ulm) and by IBM. A frequency divider of 42 Gbit/sec and a 60 Gbit/sec demultiplexer were recently realized by Siemens [22], [23]. The large scale integration (LSI) potential has been demonstrated by the fabrication of arrays with small SiGe HBT's with more than 1000 and up to 30000 devices. SiGe HBT's are nowadays also used for hybrid integration. An active antenna for a 5 – 8 GHz receiver with the excellent noise figure of 1.4 dB was reported by the University of Ulm with a SiGe HBT from us [24]. Excellent low phase noise in a 4.7 GHz oscillator has been demonstrated with –135 dBc at 10 kHz offset from carrier, another HBT had –115 dBc at 10 kHz off. Finally dielectric resonator oscillators (DRO) for 4.7 and 10 GHz and an 8 – 12 GHz VCO have been reported by DCAG together with Dornier and CNET [25], [26].

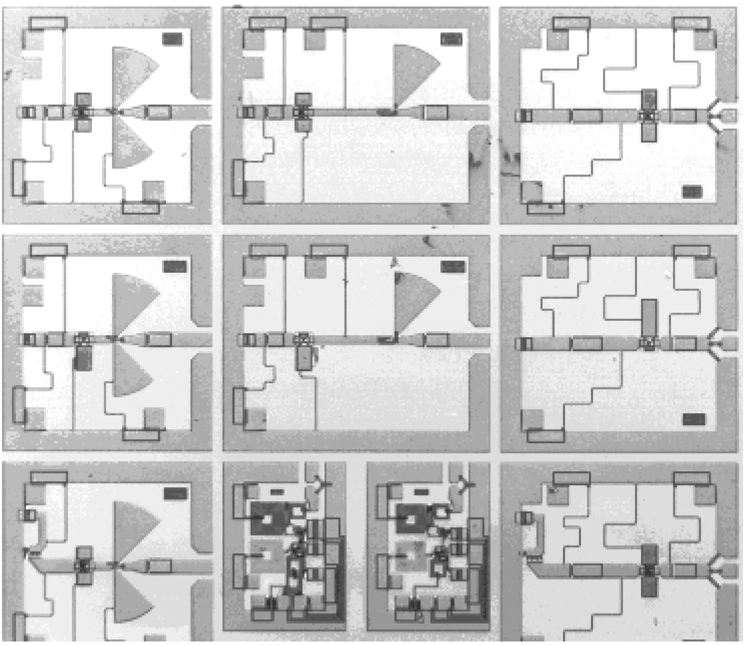
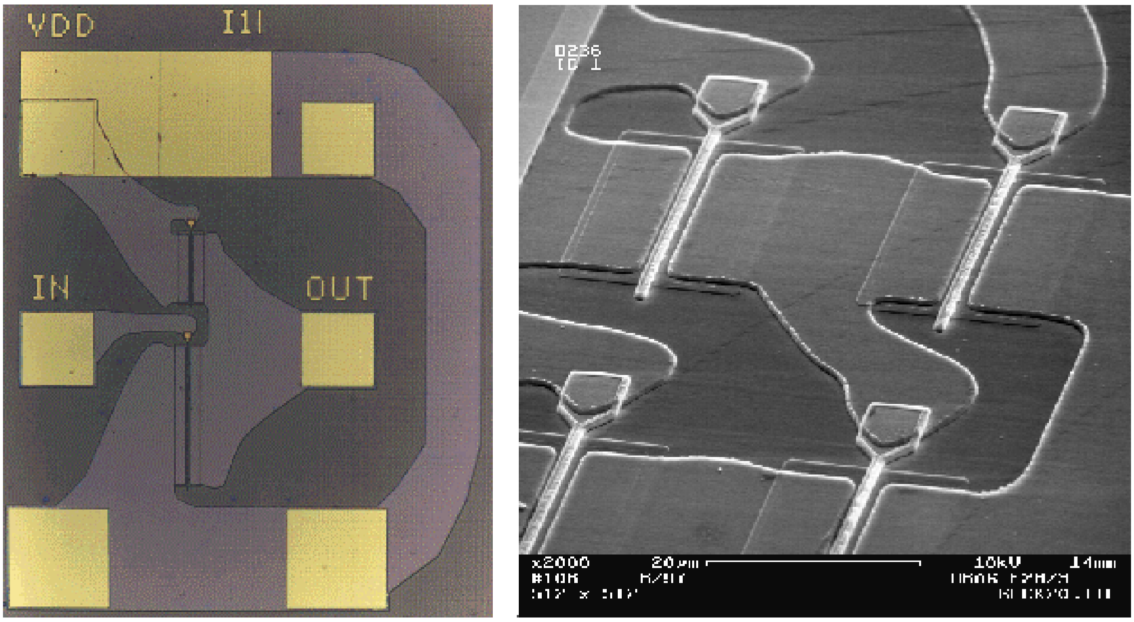


Fig. 8: SiGe HBT chip with circuits for 5 – 40 GHz

HFET circuits are far less developed. Digital and analog demonstrators are under investigation. A digital chip contains ring oscillators, inverters (shown in Fig. 9a) and level shifters (Fig. 9b). The chip technology is based on e-beam gate writing from 0.8 µm down to 0.15 µm and on two interconnect levels [27]. Very recently we have realized an transimpedance amplifier of 56 dBΩ with a –3 dBΩ frequency of 1.8 GHz. Circuits with sputter oxide passivation yield a higher transimpedance of up to 72 dBΩ with 1 GHz bandwidth. The great potential, however, lies in the integration of n-HFET's with p-HFET's to a new generation of hetero-CMOS circuits. SiGe hetero-CMOS enables the same mobility and velocity for both types of HFET's with equal geometry. Modular circuit concepts allow the integration of HFET circuits with standard VLSI-CMOS. The technology starts with conventional CMOS process including the poly gate, leaving blank areas for the heterodevices. Then the HFET processing (low temperature Si/SiGe epitaxy and oxide deposition, patterning) follows. The HCMOS circuit is then reintroduced into the CMOS lines and receives the final metallization and passivation steps. The flexibility of such a concept has experimentally already been checked [28].



(a) (b)

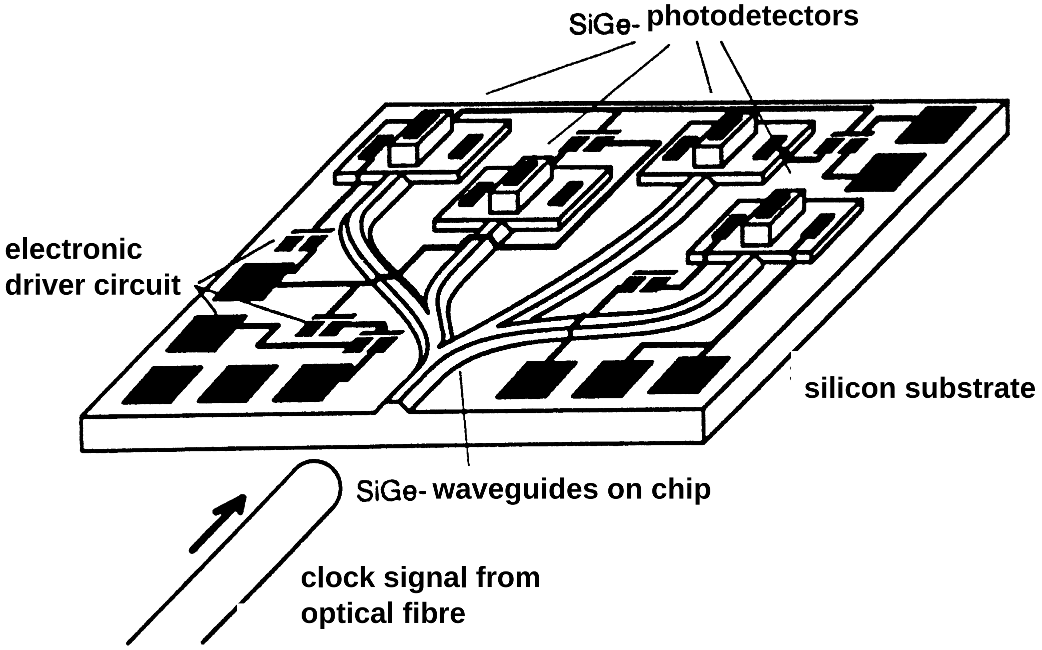
Fig. 9: (a) Inverter circuit with a resistor as load and an n-type depletion MODFET as driver [27]; (b) level shifter with n-HFET’s.

The chances for a SiGe HFET circuit fabrication are high. When the SiGe technology is implemented in Si IC factories, this infrastructure may be used for HFET circuits too. The strongest technological challenge for the future remains the realization of the ideal SiGe hetero CMOS concept. The current problems with the p-HFET technology has to be overcome with low thermal budget oxides and with defect densities related to the buffer layers. However, the outstanding performance perspectives justify the effort.

5. SiGe Optoelectronic Devices

The vision of an integrated optical circuit on a Si wafer for fiber optical communication requires Si based emitter and receiver device functions as key devices which can be monolithically integrated on a Si IC chip with e.g. a CMOS electronic driver circuit. A possible realization of interchip and intrachip coupling on a Si substrate via Si/SiGe light emitting and receiving devices can be seen in Fig 10. Figure 10 (a) depicts the distribution of an optical clock signal from an external laser via (patterned or diffused) Si waveguides to different detectors on the same chip, Fig.10 (b) shows schematically a Si based LED distributing signal via different Si waveguides, transmitting it in free space and collecting it in different waveguides on the next chip. A great impact to this field has been given by the realization of the first short-period strained layer Si_mGe_n superlattice light emitting diode which exhibited room temperature electroluminescence in the near infrared (1.3 μm) [29]. Later on room temperature electro- and photoluminescence has been measured from strained Si/SiGe quantum well layers [30]. About the same time good SiGe photodetectors with external efficiencies of $\eta \approx 12\%$ and response times of 400 nsec became available [31]. In addition, other passive optical device functions such as modulators and interferometers with SiGe waveguides have been realized on Si substrates [32] which are necessary for an integrated optical and electronic circuit on Si.

a) Concept of distribution of an external optical clock signal on an Si IC chip.



b) Concept for SiGe Optical data transmission on chip

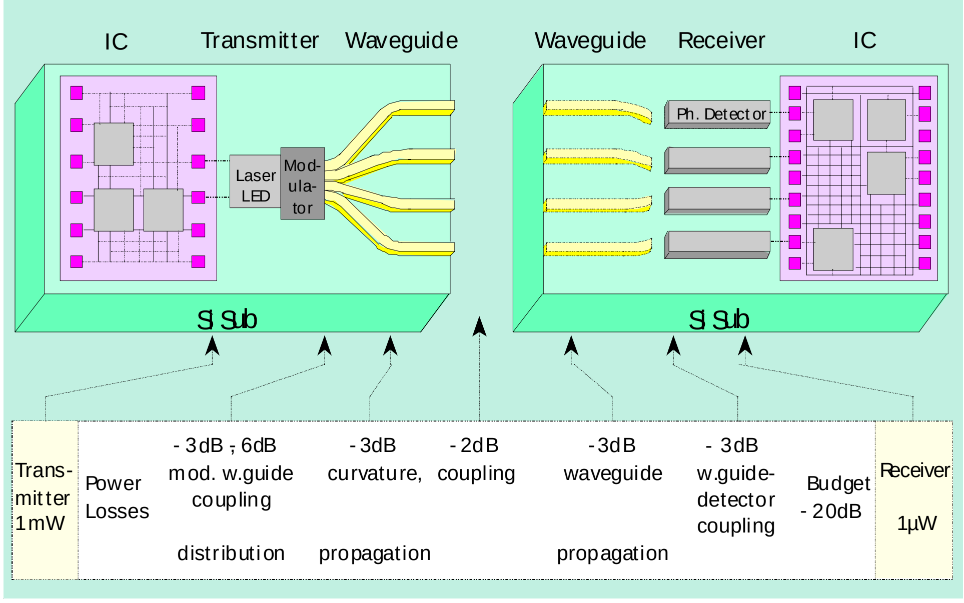


Fig. 10: (a) Concept of optical clock distribution on a Si IC chip using SiGe waveguides and photodetectors , (b) concept of optical interlink between two Si IC chips vial optical LED and detector devices.

Very recently interest has been raised on mid IR SiGe detectors – fabricated as large area focal plane arrays for thermal imaging applications in the 3 – 5 µm and 8 – 12 µm regime – to replace the conventional, commercially available silicide Schottky barrier detectors such as Pt:Si and Ir:Si. Even though these detectors – operating on the principle of hetero-internal photoemission (HIP) from photoexcited holes of a highly doped $Si_{1-x}Ge_x$ quantum well – have lower quantum efficiencies than comparable III-V detectors based on fundamental direct bandgap absorption such as HgCdTe and InSb, the advantage that these detectors can be fabricated on large scale Si substrates with good homogeneity, fill factor, and perfect thermal match to a hybrid mounted Si readout circuit overcompensates this drawback. Moreover, the use of SiGe bears the advantage of a wavelength tunable multi-color detector where the cutoff wavelength can be easily adjusted by the choice of the Ge content and/or doping level. Si/SiGe focal plane arrays have already been demonstrated with 256x256 [33] and 400x400 pixels [34] with excellent homogeneity, good dark current and external efficiencies around 0.75 %.

6. Markets for SiGe RF Devices

The turnover of microelectronic and optoelectronic devices and circuits is worldwide rapidly growing from US $45 billion in 1990, to 77$ billion in 1993 over 154 billion $ in 1995 and is estimated about 350 $ billion by the year 2000. Among all semiconductor materials Si is dominating this market with more than 97% share. 72% to 80% of this market share is covered by CMOS mainly for microcontrollers and memories.

Though the percentage share of bipolars will decrease from today to the year 2000 it means nevertheless an increase in turnover. This market trend is the biggest motivation to develop Si based hetero circuits. SiGe HBT’s and SiGe HFET’s or HCMOS fit best into the respective Si markets. SiGe HBT circuits will be introduced by the year 2000 while we hope to have a SiGe HFET ready to the market by then. Another important aspect is an economical one. SiGe needs no new fab because Si fabrication lines can be used, a fact that saves tremendously investment and processing costs. SiGe can use large Si-wafers which lowers material and area related processing costs. The area related processing costs are 0.09 $/mm^2 and 0.12 $/mm^2 for Si and SiGe [35] bipolar circuits while GaAs and InP costs go up to 0.5 $/mm^2 and 1.2 $/mm^2, respectively. SiGe hetero devices and circuits will be produced by large chip manufacturers. Companies like IBM, Siemens, NEC Philips, Hitachi, and TEMIC together with DaimlerChrysler are and will certainly stay active in this field.

Low cost, high performance Si/SiGe IC’s are ideally suited for the high volume markets. There are various communication services as shown in Fig. 11. The mobile communication (MOBICOM) transmits audio and voice via handy phones at 0.9 to 2 GHz. The wireless local area networks (WLAN) at 2.4 and 5.8 GHz connects PC’s. The satellite communication (SATCOM) at different bands (10 – 14 GHz, 25 GHz) or even higher supply low infrastructure areas and mobile users. The wideband communication via cables presently by coax and in future by fiber optic cables (FIBRECOM) transmit from 3 to 40 Gbit/s mainly in hubs of conurbation and in intercontinental networks. Each of these services will have 50 to 100 million users or terminals by the year 2005. With module system costs between $100 and $700 one expects market shares of 20 to 60 billion $ each [35]. Further markets are seen in navigation of mobile objects, e.g. global positioning (GPS ~1.5 GHz), satellite navigation (>10 GHz), defense and landing radar (20 – 40GHz), collision avoidance of cars (~70 GHz), robotic and industry sensors

(20 – 50GHz) which is sketched in Fig. 11. Market analysis also expects 100 Mio. modules for both fields. Computer and consumer electronics which increasingly demand faster signal processing might be a market for a SiGe chip. The share of microelectronic components in these systems is 20% to 40%, which makes this market attractive for chip manufacturers. According to collecting studies of different companies and market research groups the total turnover of SiGe chips in the next century is above 10 bill. US $.

Fig. 11: Scenario for applications of Si/SiGe hetero devices in the high volume communication market

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