High Speeds in a Single Chip

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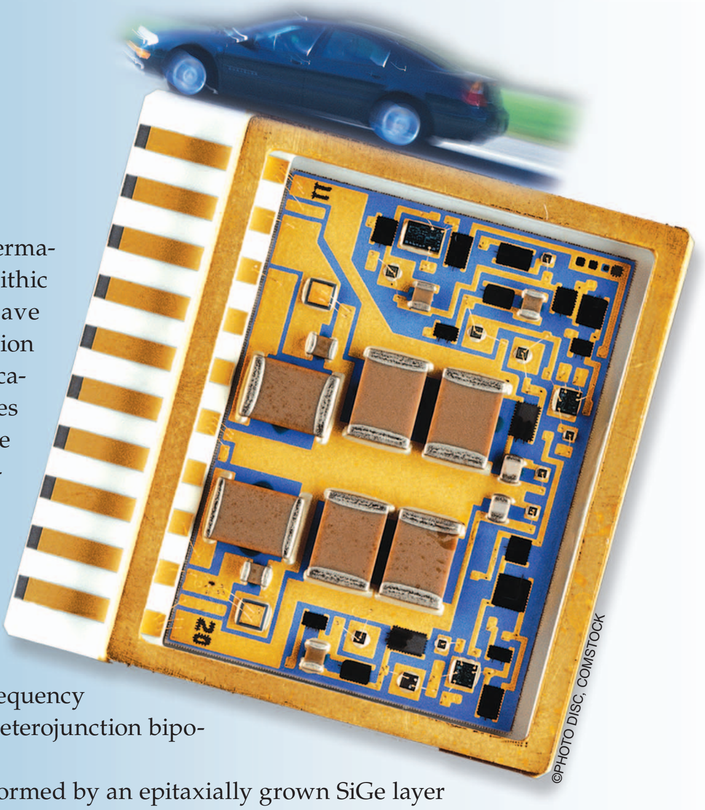
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Today, silicon (Si)- and Si-germanium (SiGe)-based monolithic integrated millimeter-wave circuits allow the realization of sensing and communication systems with operating frequencies up into the millimeter-wave range. The state of the art of today's Si based semiconductor technologies allows for low-cost fabrication of circuits with operating frequencies up to 200 GHz and opens the door for millimeter-wave consumer applications in communication technology and sensor applications. A key element of Si-based high-frequency semiconductor electronics is the SiGe heterojunction bipolar transistor (HBT).

In the SiGe HBT, the base region is formed by an epitaxially grown SiGe layer between the adjacent Si layers. Due to the lower band gap of the base region and the high base doping, a high emitter efficiency is achieved. This allows an HBT design with small base width and a low base series resistance [1]. Si-based devices allow for low-cost production and, therefore, the SiGe HBT has enabled the break-through of Si-based monolithic microwave integrated circuit (MMIC) technology and opened the market for consumer applications of millimeter waves [2].

This article reviews the development and breakthrough of SiGe technologies. SiGe-HBTs with transit frequencies f_t and maximum oscillation frequencies f_{max} above 300 GHz and monolithic integrated millimeter-wave circuits based on these HBTs have been developed by several groups [3]–[9]. As we show in the following overview, the combination of active devices with passive planar structures, including antenna elements, allows single-chip realizations of complete millimeter-wave front-ends.

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Silicon-Germanium Heterojunction Bipolar Transistor

History

A bipolar transistor with an emitter of wider energy gap than the base was already mentioned explicitly in William Shockley's original patent [10]. The HBT, however was proposed for the first time by Alfons Hähnlein [11]. In July 1954, Herbert Kroemer submitted a paper in which he formulated the idea of wide-gap emitter design [12]. He presented the theory of the wide-band emitter transistor in detail in 1957 [13], [14]. However, at that time, the technology for the realization was not available.

The growth of defect-free SiGe layers was challenging since the lattice constants differ by about 4%. Thus, SiGe films grown upon a Si substrate are compressively strained and are subject to a stability criterion according to the diagram shown in Figure 1, which plots the realizable effective layer thickness against the strain, i.e., the Ge content [15]. The green area marks the stable region in which defect-free SiGe films can be grown on Si substrate.

In 1977, Erich Kasper and Peter Russer proposed a bipolar transistor on the basis of a monocrystalline SiGe mixed crystal system and specified precise dimensioning rules and technological fabrication procedures [16]. In this patent, the double hetero-structure was proposed for the first time (Figure 2). According to this disclosure, by application of ultra-high vacuum technology to a monocrystalline Si substrate (1), first a negative- or positive-doped (n/p) Si layer (2) is grown as the collector. Then a thin p/n SiGe mixed crystal layer (3) with a thickness less than 200 nm is grown to form the base of the transistor. On this layer the Si emitter layer (6) is grown. This has been an essential step to reduce the lattice mismatch. The first realized SiGe HBT has been reported in 1987 by IBM researchers [17].

Principle

In the SiGe HBT, the base region is formed by an epitaxially grown SiGe layer between the adjacent Si layers. With increased Ge content in the base, the bandgap E_g of the base region is reduced by $\Delta E_{g,\,Ge}$, as shown in Figure 3.

Due to the lower band gap of the base region and the high base doping a high emitter efficiency is achieved. The base of an HBT can thus be more heavily doped than the base of a Si bipolar transistor to reduce the base resistance without a negative impact on the current amplification. Figure 4 shows the cross section of an HBT. HBTs are fabricated using a self-aligned emitter-base structure together with a selective epitaxial growth of the SiGe base layer. The effect of a reduced barrier on the electron injection from the emitter into the base and the corresponding design freedom regarding the emitter and the base doping becomes evident for high-frequency operation.

The unity current gain cutoff frequency f_t, also known as the *transit frequency*, is given by

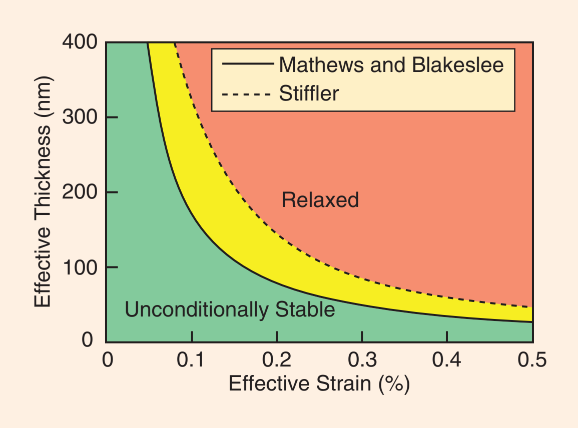

Figure 1. *Layer stability diagram of Si/SiGe heterostructures showing the realizable effective layer thickness versus the Ge content (strain) of the grown film for unconditionally stable defect-free SiGe layers on silicon [15].*

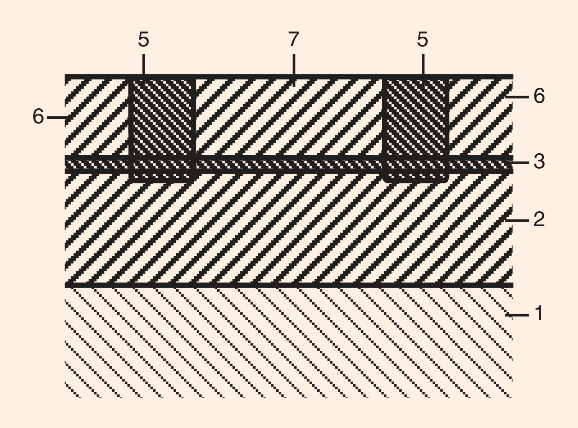

Figure 2. *Schematic of the SiGe HBT as proposed in the* disclosure [16]. *The numbers correspond to various layers used to fabricate the transistor.*

$$f_t = [r_e(C_{eb} + C_{cb}) + \tau_b + \tau_e + \tau_c]^{-1}, \qquad (1)$$

where C_{eb} and C_{cb} are the emitter-base and the collector-base depletion capacitances; τ_b, τ_e, and τ_c are the base, emitter, and collector transit times; and the emitter resistance r_e is given by

$$r_e = \frac{kT}{eI_c}. \qquad (2)$$

When de-embedded S-parameter measurements are made, it is not this ideal inner transistor but a transistor with series resistances to the three contacts (emitter, base, collector) that is measured [18]. The maximum oscillation frequency f_{max} of the HBT is given by

$$f_{max} = \sqrt{\frac{f_t}{8\pi C_{bc} r_b}}, \qquad (3)$$

where r_b is the base resistance, and C_{bc} is the base collector capacitance. In SiGe HBTs, the lower bandgap allows for a high base doping and, therefore, a low-base resistance, which increases f_{max}.

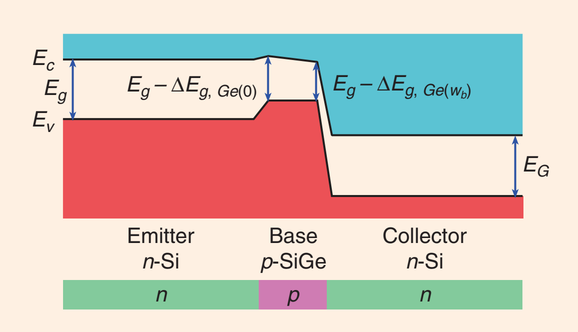

Figure 3. *Band structure of a SiGe heterojunction bipolar transistor. Due to the lower bandgap of the SiGe base region, a higher base doping with lower base resistance in comparison to Si bipolar transistors can be achieved.*

The usual transistor paradigm is based on broad-band signal amplification from low frequencies up to f_t. Phase shift between input and output of the transistor leads to the loss of amplification. Luryi [19] suggested a coherent transport in transistors to overcome the phase shift limitations. Investigations of the resonance phase transistor, combining a coherent transport with a depletion layer phase delay, resulted in the first experimental verification of a power gain of the resonance phase transistor beyond its transit frequency [20]–[22]. The resonance phase transistor is a SiGe HBT in which current amplification is achieved far beyond the transit frequency on the basis of a coherent carrier transport in the base region. This allows one to design transistors with a higher base width for a given operating frequency and can increase the RF output power by a factor of ten.

Monolithic Integrated Millimeter-Wave Circuits

Linear Amplifiers

The evolution of SiGe processes is reflected well in the increasing performance of amplifiers in the millimeter-wave regime. W-band (75–110 GHz) amplifiers in SiGe technology have recently been reported in the literature [23]–[25].

A 91 GHz low-noise amplifier (LNA) using a unilateral gain peaking design technique was presented in [23]. The LNA was developed in a 0.12 μm, 200 GHz f_t SiGe technology. Measured results demonstrated a peak gain of 13 dB, an IIP3 of −5.4 dBm, and a noise figure of 5.1 dB with a dc power consumption of only 8.1 mW at 91 GHz. The amplifier exhibits a 3 dB gain bandwidth of 16 GHz from 84 to 100 GHz, with a minimum gain of 10 dB and an average noise figure of only 5.5 dB.

An ultra-wideband amplifier scheme was realized in [26] with two cascaded stages that are equalized for high-bandwidth and low-gain ripple. The amplifier was implemented in a 0.12 μm SiGe bipolar complementary metal-oxide-simiconductor (BiCMOS) process and achieves a 3 dB bandwidth of 102 GHz. A gain of 10 dB was reported with less than 1.5 dB gain-ripple and group-delay variation under 6 ps over the entire 3 dB bandwidth. The chip occupies an area of 0.29 mm^2 including the pads and consumes 73 mW from a 2 V supply.

Oscillators

SiGe bipolar technologies are well-suited for voltage-controlled oscillators (VCOs) in the millimeter-wave regime due to their higher output power and better phase noise performance in comparison to CMOS.

Fully integrated SiGe VCOs with an output buffer for 77 GHz automotive radar systems and applications around 100 GHz were realized in [27]. The corresponding chip photograph is depicted in Figure 5. At a center frequency of 77 GHz, a tuning range is achieved of 6.7 GHz with a phase noise of −97 dBc/Hz at 1 MHz offset frequency. The total signal power delivered by both buffer outputs together is 18.5 dBm.

A fully monolithically integrated J-band (220–325 GHz) push-push oscillator was presented in [28]. The device was fabricated in a production-near SiGe:C bipolar technology. The transistors used in the work showed a maximum transit frequency f_t of 200 GHz and a maximum frequency of oscillation $f_{\max}$ of 275 GHz. The passive circuitry was realized by integrated transmission-line components, metal-insulator-metal-capacitors, and TaN resistors. The frequency of the output signal can be tuned between 275.5 GHz and 279.6 GHz.

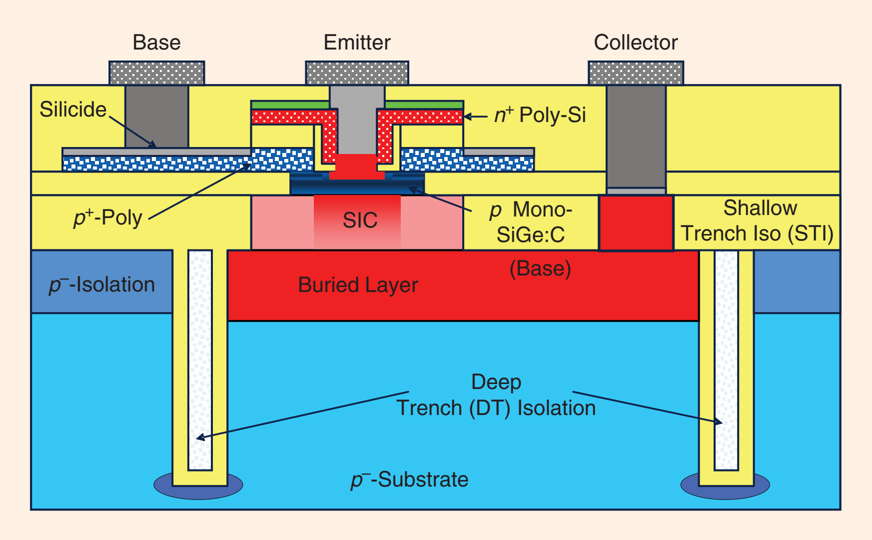

Figure 4. *Cross sectional view of a SiGe npn heterojunction bipolar transistor with self-implanted collector (SIC) and deep trench isolation.*

Power Amplifiers

A 77 GHz, 17.5 dBm power amplifier (PA) with fully integrated 50 Ω input and output matching was fabricated in a 0.12 μm SiGe BiCMOS process [29]. It achieves a peak power gain of 17 dB and a maximum single-ended output power of 17.5 dBm with a 12.8% power-added efficiency (PAE). The PA has a 3 dB bandwidth of 15 GHz and draws 165 mA from a 1.8 V supply. Conductor-backed coplanar waveguides were used as the transmission line structure, which results in a large isolation between adjacent lines, and enables the integration of the PA in an area of 0.6 mm^2.

A +20 dBm PA for applications in the 60 GHz industrial scientific medical (ISM) band was presented in [30]. The PA was fabricated in a 0.13 μm SiGe BiCMOS process technology and features a fully integrated on-chip root mean square (RMS) power detector for automatic level control (ALC), built-in self test and voltage standing wave ratio (VSWR) protection. The single-stage push-pull amplifier uses center-tapped microstrips for a highly efficient and compact layout with a core area of 0.075 mm^2. The PA delivers up to 20 dBm without the need for power combining. At 60 GHz, it achieves a peak power gain of 18 dB, a 1 dB compression of 13.1 dBm, and a peak PAE of 12.7%. The amplifier is programmable through a three-wire serial digital interface enabling an adaptive bias control from a 4 V supply.

Mixers and Receivers

An active down-conversion mixer for automotive radar applications from 76 GHz to 81 GHz was realized in a 200 GHz f_t SiGe bipolar technology [31]. The chip photograph is shown in Figure 6. A conversion gain of more than 24 dB and a single-sideband noise figure of less than 14 dB is achieved. The 1 dB output compression point is −4 dBm. The power consumption is 300 mW at −5 V supply voltage.

In [32], a single-chip receiver front end was presented, consisting of a low-noise amplifier and an active down-conversion mixer at 77 GHz. A die photograph is shown in Figure 7. The circuit was implemented in a SiGe:C HBT technology with $f_t/f_{\max} = 200/250$ GHz and can operate either fully differential or in single-ended mode. The front end shows a conversion gain of 24 dB and a single sideband noise figure of 14 dB when driven single-ended. Linearity measurements show a 1 dB input-related compression point of −10 dBm. The circuit draws 40 mA from a 3.3 V supply and occupies a chip area of 728 × 1,028 μm^2.

Frequency Dividers

Static and dynamic frequency dividers were realized in a 200 GHz f_t SiGe bipolar technology [33]. The static divider has a divide ratio of 32 and operates up to 86.2 GHz. Figure 8 shows the chip photograph of the static divider. The dynamic divider is based on regenerative frequency division and has a divide ratio of two. It operates up to 110 GHz (limited by the measurement equipment).

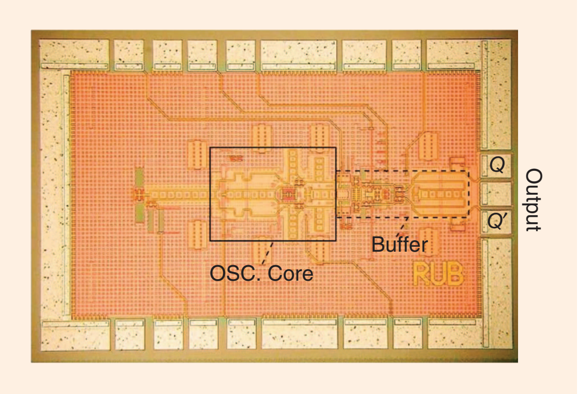

Figure 5. *Die photograph of the 77 GHz SiGe fundamental oscillator with output buffer and 6.7 GHz tuning range for automotive radar applications* [27].

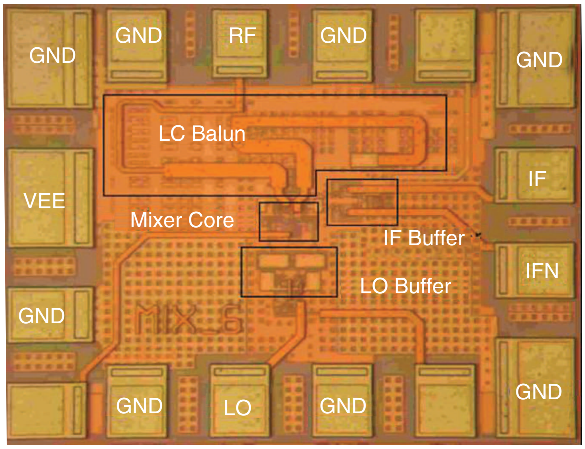

Figure 6. *Die photograph of the single-ended 77 GHz active down-conversion mixer with integrated LC balun and local oscillator (LO) buffer in SiGe technology [31].*

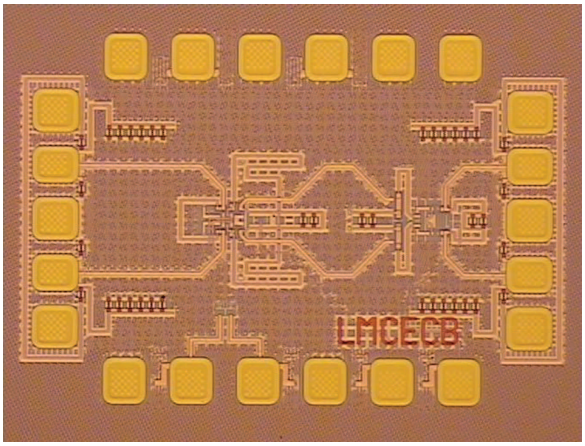

Figure 7. *Die photograph of the 77 GHz receiver front-end in SiGe technology which can operate either fully differential or in single-ended mode [32].*

A double mixer in [34] was used to directly divide the input frequency by four. A validation chip had been developed in a 225 GHz f_t SiGe bipolar technology. The circuit operates in a frequency range of 80–160 GHz with a power consumption of 650 mW from a −5.5 V supply.

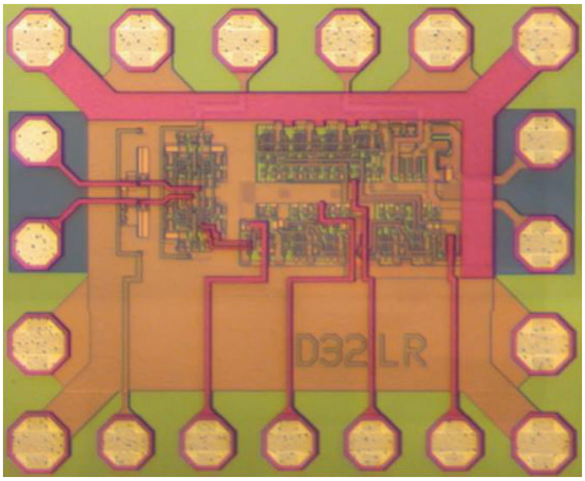

Figure 8. *Die photograph of the static frequency divider operating up to 86 GHz with a divide ratio of 32 in a 200 GHz f_t SiGe technology [33].*

Systems on Chip

The feasibility of monolithic single-chip solutions for millimeter-wave transceiver front ends has been demonstrated by several groups. Figure 9 shows the die photograph of a fully integrated four-channel 77 GHz transceiver in SiGe [35]. The chip area is $3.25 \times 2.1\ \mu m^2$. It consists of a fundamental VCO with PA and frequency divider. The chip features four mixers with two rat-race couplers and LO signal distribution. With a transmit power of $2 \times +7$ dBm at the antenna ports, the chip consumes 600 mA from a single 5.5 V supply. The gain of the isolated and transfer receivers is 14.2 and 8.5 dB, with a noise figure of 17.7 and 23.4 dB, respectively.

A SiGe HBT single-chip direct-conversion 77−85 GHz transceiver for Doppler radar and millimeter-wave imaging was reported in [36]. The chip has been fabricated in a 0.13 μm technology with $f_t/f_{\max}$ of 230/300 GHz. It achieves 40 dB conversion gain in the receiver at 82 GHz, a 3 dB bandwidth extending from 77 to 85 GHz and 3.85 dB double-sideband noise figure at an LO frequency of 82 GHz.

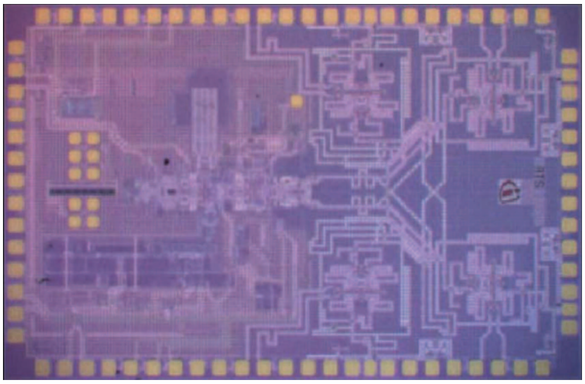

Figure 9. *Die photograph of the first four-channel 77 GHz radar transceiver in an automotive environment certified SiGe production technology [35].*

SiGe HBT D-band (110–170 GHz) transceivers transmitting simultaneously at 80 GHz and 160 GHz were reported in [37]. The transceivers feature a 80 GHz quadrature Colpitts oscillator with differential output at 160 GHz and broadband 70 to 180 GHz vertically stacked transformers. A peak differential down-conversion gain of −3 dB has been achieved at 165 GHz. The single-ended 165 GHz transmitter generates −3.5 dBm, while the 82.5 GHz differential output power is +2.5 dBm.

Antenna Integration on Chip

For circuits with operational frequencies of 60 GHz and above, the small wavelength permits additional integration of antennas on the chip. This alleviates the problem of high-frequency transitions from the circuit to the periphery. The performance of such planar antennas is mainly limited by the permittivity of the Si substrate.

In [38], a fully integrated 77 GHz four-element phased-array transceiver with on-chip antennas in Si was presented. The peak measured antenna gain of a single integrated dipole antenna is 2 dBi.

A single-chip 165 GHz transceiver with on-die transmit and receive antennas was reported in [39]. Investigations on the performance of integrated patch and tapered dipole antennas above floating metal strips have been carried out, yielding an antenna loss of 25 dB.

Conclusion and Outlook

Today, Si- and SiGe-based monolithic integrated circuits allow the realization of sensing and communication systems with operating frequencies into the millimeter-wave range. Combining active devices with passive planar structures, including antenna elements above 60 GHz, allows single-chip realizations of complete millimeter-wave front-ends using SiGe HBTs. Complete monolithic integration of 77−81 GHz automotive radar front-ends is already feasible today.

In the future, Ge-based RF-MOS and high-speed optoelectronic links based on Si-on-insulator (SOI) waveguides and Ge photodetectors and modulators will enter the mm-wave regime. Photodetectors from epitaxial Ge on Si proved speeds up to 50 GHz, with a potential well above 100 GHz. Their good detection and modulation behavior in the near-infrared are a prerequisite for on-chip waveguide solutions.

Detailed information on the high-frequency behavior of Si-based micro-, mm-wave, and terahertz solutions will be presented at the next Topical Meeting on Si Monolithic Integrated Circuits in RF Systems (SiRF2010) in New Orleans (www.silicon-rf.org). SiRF2010 will treat materials, devices, IC technologies, circuits, passives, MEMS/NEMS, reliability issues, measurement and modeling, applications, and nanoscale microwave solutions.

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