Si and SiGe Millimeter-Wave Integrated Circuits

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(Invited Paper)

***Abstract*—Monolithic integrated millimeter-wave circuits based on silicon and SiGe are emerging as an attractive option in the field of millimeter-wave communications and millimeter-wave sensorics. The combination of active devices with passive planar structures, including also antenna elements, allows single-chip realizations of complete millimeter-wave front-ends. This paper reviews the state-of-the-art silicon- and SiGe-based monolithic integrated millimeter-wave circuits. The technological background as well as active and nonlinear devices and passive circuit structures suitable for silicon- and SiGe-based monolithic integrated millimeter-wave circuits are discussed. Examples of such integrated circuits and first systems applications are also presented.**

***Index Terms*—Millimeter-wave IC, silicon-based RF circuits.**

I. Introduction

MILLIMETER-WAVE sensor and communication applications as well as fast data processing create an increasing demand in high-frequency electronic devices and monolithic integrated circuits. Silicon is by far the most widely used semiconductor material, and there are good reasons that this situation will not change in the future. In production, silicon is preferred due to low costs, established production lines, the high standard of technological experience, and a number of technological advantages. This yields a strong impact to overcome the drawbacks of standard silicon devices in the millimeter-wave range.

In 1965, Hyltin had already proposed the use of silicon as the dielectric substrate for planar microwave circuits [1]. Silicon-based monolithic integrated millimeter-wave circuits have been suggested in 1981 by the RCA group of Rosen *et al*. [2]. Since 1986, in the field of silicon monolithic millimeter-wave integrated circuits (SIMMWIC's) there are increasing research activities at the former AEG-Telefunken Research Institute, which has merged now into the Daimler-Benz Research Center, Ulm, Germany, and at the Technische Universität München, Munich, Germany [3]–[8]. Up to now, SIMMWIC's for frequencies above 100 GHz have already been fabricated, and the suitability of silicon as the substrate material for monolithic integrated millimeter-wave circuits has been successfully demonstrated. Monolithic integration of solid-state devices provides the possibility of low-cost production, improved reliability, small size and light weight, and easy assembly.

There is a variety of active semiconductor devices suitable for SIMMWIC's. The SiGe heterojunction bipolar transistor (HBT) is a promising candidate for silicon-based monolithic integrated millimeter-wave circuits [8]. Ultra-fast silicon bipolar technology also gives a strong impact on the development of high-speed digital and analog circuits [9]–[11]. For SIMMWIC's, the IMPATT diode provides high oscillator-output power combined with high efficiency.

The linear passive parts of SIMMWIC's may be realized in planar circuit technology. The fundamental transmission-line structures used in SIMMWIC design are microstrip lines, slot lines, coplanar lines, coplanar striplines, and microshield lines. Based on these fundamental geometric structures, the planar circuit elements are designed. These planar circuit elements include transmission-line discontinuities, planar resonators, and antennas as the basic structures. In the frequency region above 60 GHz, SIMMWIC's of only a few millimeters size may also include planar antenna structures. The integration of the antenna allows the direct coupling of SIMMWIC's to the radiation field.

Monolithic integrated millimeter-wave circuits based on silicon and SiGe will give new options for millimeter-wave sensor and communication applications. Compared with microwave-based systems, millimeter-wave-based systems offer the following advantages:

1) availability of broader frequency bands;
2) higher gain and smaller dimensions of antennas;
3) smaller size and lower weight of the components;
4) due to the shorter wavelength, higher resolution in sensor applications;
5) atmospheric attenuation may prevent interference between cells in communication applications.

A broad application of millimeter waves in sensorics and communications has been hampered up to now due to the high costs of millimeter-wave components. This situation may change in the future due to the availability of low-cost monolithic integrated components. Especially a silicon and SiGe-based technology can promote further cost reduction of monolithic integrated millimeter-wave circuits.

II. Silicon as the Substrate Material

Today, silicon substrate material with a specific resistance of $10\,000\ \Omega \cdot \mathrm{cm}$ is available. For this material in planar circuits, the conductor losses due to the skin effect dominate the loss contributions, whereas the substrate losses in the silicon account only for a minor part. A further comparison of the data of Si and GaAs according to Table I shows the excellent feasibility of silicon as the base material for millimeter-wave circuits. The dielectric constant of both materials is

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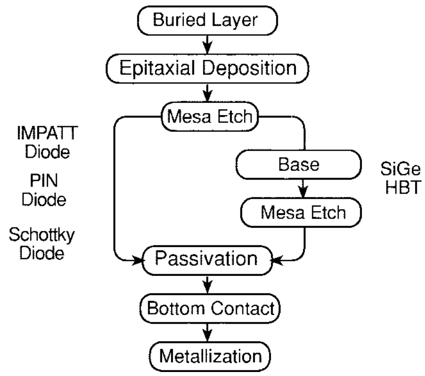

Fig. 1. Schematic process flow.

TABLE I
PARAMETERS OF Si AND GaAs

	Si	GaAs
Diel. Const.	$\epsilon_r = 11.7$	$\epsilon_r = 12.9$
Specific Resist.	$> 10^4\ \Omega$ cm	$> 10^6\ \Omega$ cm
Dielectric Loss Factor (90 GHz)	$1.3 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
Thermal Cond.	1.45 W $cm^{-1}K^{-1}$	0.46 W $cm^{-1}K^{-1}$
Electron Mobility	700 cm^2/Vs	4300 cm^2/Vs
High Field Drift Velocity	10^7 cm s^{-1}	$6 \cdot 10^6$ cm s^{-1}
Density	2.33 g cm^{-3}	5.32 g cm^{-3}

comparable. At 90 GHz also, the dielectric loss tangents of Si and GaAs are within the same order of magnitude. Although the electron mobility of GaAs is six times higher than the electron mobility of Si, the high-field drift velocity of Si and GaAs are in the same order of magnitude. In most millimeter-wave semiconductor devices, the high-frequency performance depends mainly on the high-field drift velocity, whereas the electron mobility plays a minor role. The thermal conductivity of silicon is three times higher than the thermal conductivity of GaAs. From this point of view, silicon is advantageous for power circuits. Fig. 1 shows the schematic process flow of a SiGe/SIMMWIC technology which allows the fabrication of Schottky diodes, IMPATT diodes, SiGe HBT's, and p-i-n diodes [8].

Since SIMMWIC's require high-resistivity substrates, whereas integrated circuits based on standard bipolar, CMOS, and BICMOS technologies need low-resistivity substrates, a combination of these technologies is not straightforward. However, a combined SIMMWIC and CMOS technology has already been introduced in [12].

III. ELECTRONIC DEVICES

A. Pure Silicon Bipolar Transistors

Ultra-fast silicon bipolar technology also gives a strong impact on the development of high-speed circuits [9]–[11]. Today, high-performance bipolar technologies are mainly based on double-polysilicon self-aligned structures, as first described in [13] and [14]. In the BICMOS technology, the combination of self-aligned structures and oxide insulation allows an extreme downscaling, and also the realization of extremely low parasitic capacitances. As an example for a high-speed Si bipolar transistor structure, Fig. 2 shows a bipolar transistor in selective epitaxial growth (SEG) technology [15]. Böck *et al.* have presented a 50-GHz implanted-base Si bipolar technology for mixed digital and analog applications [16], [17].

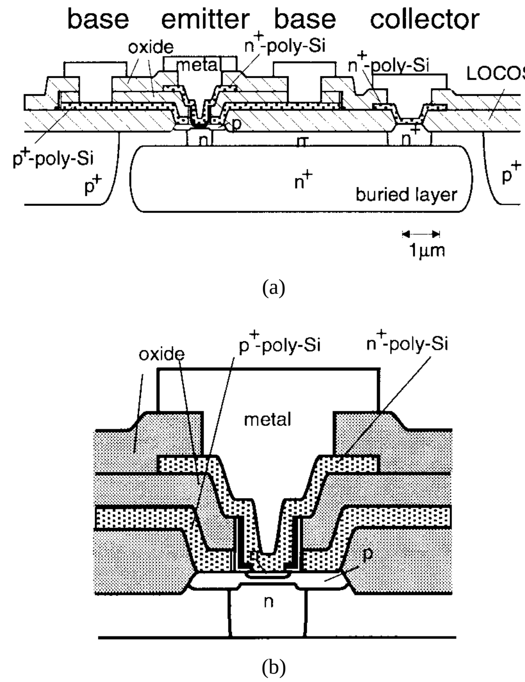

Fig. 2. (a) Bipolar transistor. (b) Magnified part.

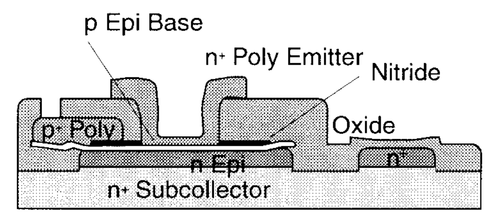

Fig. 3. Cross section of SiGe HBT.

A. SiGe-Base HBT's

A promising device for millimeter-wave applications is the SiGe-base HBT [18]. The HBT had been first suggested in 1957 by Kroemer [19]. A first suggestion for a SiGe-base HBT for high-frequency applications had been made in 1977 [20], [18]. Detailed investigations of the millimeter-wave SiGe-base HBT were presented by [21]–[29]. Fig. 3 shows the cross section of an HBT.

In the SiGe HBT, the base region is formed by an epitaxially grown SiGe layer between the adjacent silicon layers. Due to the lower bandgap of the base region, even in the case of high base doping, a high emitter efficiency is achieved. This allows one to combine small base width with a low base series resistance.

In the SiGe-base HBT, the base is formed by an epitaxially grown SiGe layer. By this way, the bandgap in the base region is reduced compared with the bandgap in the emitter region. The current gain β of a conventional bipolar transistor is given by

$$\beta = \frac{D_{nE} N_E w_E}{D_{pB} P_B w_B} \tag{1}$$

where D_n and D_p are the diffusion constants of electrons and holes in the emitter and base regions, respectively, N_E and P_B are the emitter and base doping concentrations, w_E is the emitter thickness, and w_B is the base thickness. For the HBT after Kroemer [19], the current gain β is given by

$$\beta = \frac{D_{nE} N_E w_E}{D_{pB} P_B w_B} e^{\Delta E/kT} \tag{2}$$

where ΔE is the bandgap difference between Si and SiGe. The exponential dependence of the minority carrier injection rate across the emitter base barrier on the bandgap difference already yields at Ge contents of 20%, a value of the exponential term of more than 1000. This allows one to obtain a high emitter efficiency also in the case of a high base doping. Due to the high base doping, low base sheet resistances with base width down to 10 nm are attainable. A typical high-frequency silicon bipolar transistor with a base width of less than 100 nm exhibits base sheet resistances in the order of 10 kΩ, whereas SiGe HBT's reach base sheet resistances as low as 1 kΩ for a 20-nm doped base [8]. A high current gain and a low base resistance may, therefore, also be combined in the case of extremely low base widths.

The transit frequency f_T of a bipolar transistor is given by [18]

$$f_T = \frac{1}{2\pi\tau_{EC}} \tag{3}$$

with the total delay τ_{EC} given by

$$\tau_{EC} = \tau_E + \tau_{E'} + \tau_B + \tau_C + \tau_{C'}. \tag{4}$$

The emitter delay time τ_E due to the minority carrier injection from the base into the emitter is in the order of 0.5–2 ps [30]. The emitter charging time $\tau_{E'}$ is in the order of a few tenths of picoseconds [18]. For no accelerating in the base, the base transit time τ_B is given by

$$\tau_B = \frac{w_B^2}{2D_n} + \frac{w_B}{v_s} \tag{5}$$

with the base width w_B and the high-field drift velocity v_s. The collector transit time τ_C is given by

$$\tau_C = \frac{x_c}{2v_s} \tag{6}$$

and the collector charging time $\tau_{C'}$ is given by

$$\tau_{C'} = C_{BC}(R_E + R_C + V_T/I_C). \tag{7}$$

The fabrication of a heterojunction bipolar SiGe transistor with f_T values above 80 GHz has already been reported [8], [18], [24], [31]–[33].

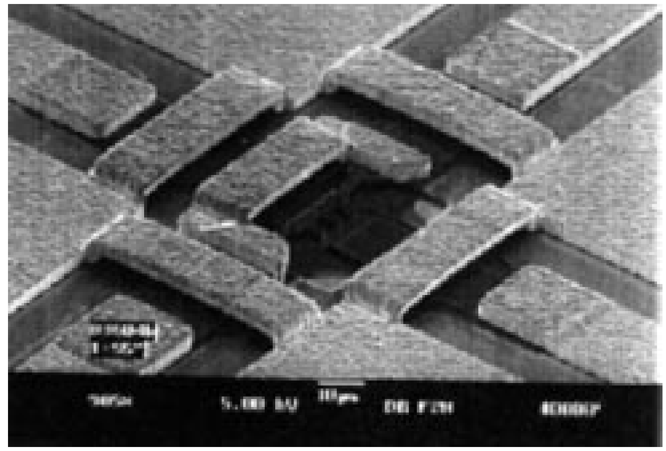

Fig. 4. SiGe HBT in coplanar line crossing.

The maximum oscillation frequency $f_{\max}$ of the HBT is given by

$$f_{\max} = \sqrt{\frac{f_T}{8\pi C_{\rm bc} r_b}} \tag{8}$$

where f_T is the transit frequency, r_b is the base resistance, and $C_{\rm bc}$ is the base collector capacity. SiGe HBT's maximum oscillation frequencies of 120 GHz already have been realized [31]. Coplanar monolithic microwave integrated circuits (MMIC's) based on SiGe HBT's with $f_{\max}$ values as high as 80 GHz are under development [34]–[36]. Fig. 4 shows an SiGe HBT embedded in a coplanar line crossing. Meister *et al*. have described an epitaxial SiGe-base HBT technology suitable for analog as well as digital applications [37].

Since HBT's exhibit optimum operating conditions at high collector current densities, the Kirk effect becomes important [18]. When the injected electron concentration exceeds the collector doping in conventional bipolar transistors, holes will accumulate in the collector region to compensate the excess charge. This causes a widening of the base and thereby a decrease in current gain and transit frequency. In SiGe HBT's, the Kirk effect is different. Due to the base–collector heterojunction, the injection of holes into the carrier is suppressed. For the large signal modeling of SiGe HBT circuits, a nonlinear HBT model that includes nonideal leakage currents, the Kirk effect, and the thermal behavior has been presented in [38].

The noise figure of a bipolar transistor may be approximated by [39]

$$F = 1 + \frac{1}{R_s}\left[r_b + \frac{r_e}{2} + \left(\frac{1}{\beta} + \frac{f^2}{f_T^2}\right)\frac{r_b^2 + R_s^2}{2r_e}\right] \tag{9}$$

where F is the noise figure, R_s is the source impedance, β is the current gain and $r_e = kT/eI_c$ is the emitter resistance. The high f_T and the low base resistance of SiGe HBT's yield a low noise figure. SiGe HBT noise figures as low as 0.5 dB at 2 GHz, 0.9 dB at 10 GHz, and 2 dB at 20 GHz have already been reported [40].

Low-frequency noise in active devices is a serious design constraint for millimeter-wave oscillator and mixer applications. Since the low-frequency noise is upconverted by the

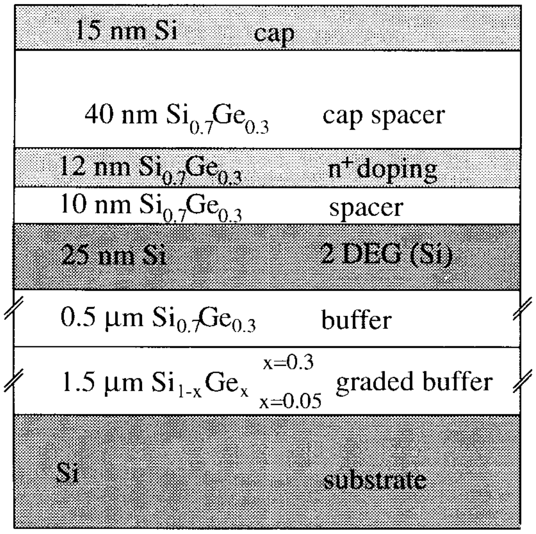

Fig. 5. Layer structure of an n-type Si/SiGe hetero FET.

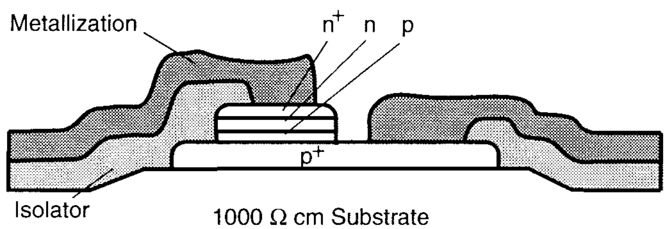

Fig. 6. Cross section of a coplanar IMPATT diode.

inherent nonlinearities of the active device, the low-frequency noise of the active device has to be minimized. The low-frequency noise in millimeter-wave Si/SiGe HBT's has been investigated in [41]–[43]. Comparison of the low-frequency noise properties of Si and SiGe bipolar transistors has shown that SiGe transistors exhibit three-to-four times smaller low-frequency noise than Si devices [44]. For an SiGe HBT with an f_T of 43 GHz, Cressler *et al*. have reported a corner frequency of 373 Hz for the $1/f$ noise at a bias current of 2.25 μA [43]. However, in real circuit applications, the bias currents are at least one order of magnitude higher and the corner frequency increases correspondingly.

C. Si/SiGe Hetero FET's

Si/SiGe heterostructure technology may also be combined with Si CMOS technology [24], [45]. Most of the Si/SiGe hetero FET's are of the modulation-doped type. These so-called MODFET's exhibit a thin quantum-well layer with a thickness of 5–30 nm. Within the quantum-well layer, a two-dimensional (2-D) electron or hole gas with collision-free carriers exists. The n-quantum wells are Si layers, whereas the p-quantum wells are formed by SiGe layers. Fig. 5 shows the layer structure of an n-type Si channel Si/SiGe hetero FET.

An $f_{\max}$ of 81 GHz has been found for a 0.18-μm T-gate n-MODFET [46]. Performance extrapolation of n- and p-channel devices point to transconductances above 1000 mS/mm and cutoff frequencies around 200 GHz [45].

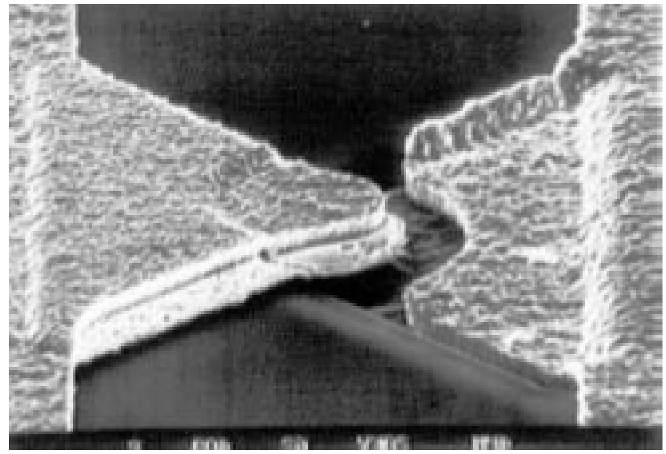

Fig. 7. Coplanar IMPATT diode.

D. IMPATT Diodes

Presently, the IMPATT diode is the most important active device for SIMMWIC's. The IMPATT diode is biased above the threshold for impact ionization. The carrier generation in connection with the transit time delay arising from the drift process causes a dynamic negative resistance [47]–[49]. The IMPATT diode provides high oscillator output power combined with high efficiency. Since the high-field drift velocity of Si and GaAs are in the same order, silicon is suited for IMPATT diodes as well as GaAs.

The negative real part of the IMPATT diode impedance is in the order of 1–10 Ω. For this reason, a low-impedance termination of the IMPATT diode is required in order to achieve oscillator operation [50]. Especially in the case of planar resonators, due to the low Q value of these resonators, a careful oscillator design is required. IMPATT diodes usually have to be thinned to a few micrometer in order to obtain a low series resistance and a good thermal conductivity. In the case of discrete IMPATT diodes, the electrical contacts are formed on both sides of the contact. Using this geometry in monolithic circuits requires substrate thinning in the region of the IMPATT diode. This can be done in principle by selective etching.

For monolithic integration of IMPATT diodes, a coplanar device structure is advantageous [51], [52]. Fig. 6 shows the cross section, and Fig. 7 shows the microphotograph of a coplanar IMPATT diode. The pnn^+ layers of the double drift-region diode are grown by molecular beam epitaxy on a highly p^+ doped etch stop and contact layer. This layer has also been grown epitaxially on high-resistivity silicon. In order to obtain a low series resistance, large p^+ contact areas are defined in a photoresist process. After passivation of the individual diodes and opening of the contact windows, the contact and planar circuit metallization is formed by evaporating gold and increasing the thickness of the gold layer to 3 μm by electroplating.

For SIMMWIC applications, the double low–high–low (DLHL) diode following the original Read diode approach is very promising [8]. Compared with conventional IMPATT diodes, the absolute value of the (negative) real part of the DLHL diode impedance is increased by more than a factor of

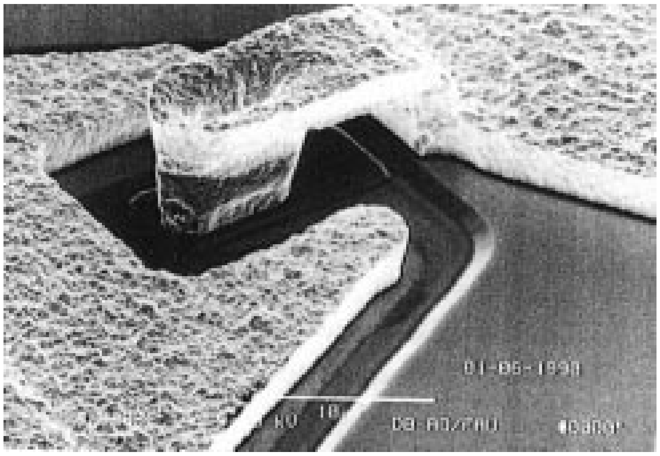

Fig. 8. Schottky diode with air-bridge.

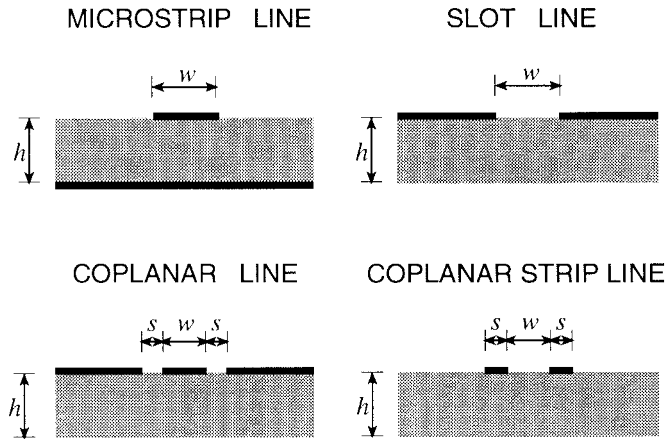

Fig. 9. Planar transmission lines.

two. This will improve the matching of the diode to planar resonators.

An IMPATT oscillator is formed by an IMPATT diode connected to a resonator. With IMPATT diodes, oscillators with high output power and high efficiency may be realized. At an oscillation frequency of 100 GHz, efficiencies above 10% may be achieved. Since monolithic integrated circuits usually exhibit a higher thermal resistance, the high efficiency of IMPATT diodes is advantageous. However, especially if planar resonator structures are used, a careful design is required in order to fulfill the oscillation condition. For the monolithic integration of IMPATT diodes, a coplanar diode structure is advantageous. Monolithic integrated IMPATT oscillators yield output powers in the milliwatt region at 100 GHz.

E. Schottky Diodes

Schottky diodes are used for detector and mixer applications in SIMMWIC receiver modules [53]. The Schottky diode consists of a n-doped layer ($10^{17}\,\mathrm{cm}^{-3}$) grown on a highly n^+-doped buried layer. A delta-doping spike on top of the epitaxially grown layer reduces the Schottky barrier formed by the titanium–gold metallization. The cutoff frequency f_c depends on the junction capacitance C_j and the series resistance R_s and is given by

$$f_c = \frac{1}{2\pi R_s C_j}. \tag{10}$$

Zero-bias operation is possible and the diodes can be monolithically integrated in microstrip or coplanar circuits [54]. Monolithically integrated Schottky diodes have been realized in a coplanar configuration [55], [56]. Coplanar Schottky diodes allow a coplanar circuit design without via holes through the substrate. At coplanar AsP-doped Schottky diodes with a junction area of 33 μm, a series resistance of 2.6 Ω, and a junction capacity of 59 fF were measured. From these values, a cutoff frequency greater than 1 THz is evaluated.

Fig. 8 shows the microphotograph of a Schottky diode with air-bridge. The air-bridge technology provides a lower parasitic capacitance and a lower leakage current.

IV. Passive Circuits on Silicon

A. Planar Circuits

With planar-circuit-structures resonators, filter circuits, power dividers, matching networks, and planar antennas may be realized [6], [57]–[59]. It is possible to combine different functions, e.g., the patch-antenna structure of an SIMMWIC transmitter may also serve as the resonator of the IMPATT diode oscillator. By this way, circuits with extremely small dimensions can be realized and, furthermore, losses in a connection line between oscillator and antenna are avoided.

Since for highly insulating silicon material for millimeter-wave frequencies the dielectric losses in the silicon play a minor role compared with the conductor losses, the use of silicon yields no drawbacks. Experimental investigations have shown that on substrates with 195-μm thickness, microstrip lines with an attenuation as low as 0.6 dB/cm can be realized [4]. Epitaxial layers have to be removed by etching in the areas of planar circuits in order to obtain these low attenuation values. Parasitic effects induced by passivation of high-resistivity silicon substrates play an important role and have to be minimized in order to obtain low loss [34]. The common types of planar transmission lines are summarized in Fig. 9.

The main concepts of planar circuit design are based on either the microstrip concept or the coplanar line concept. Microstrip circuits require thinned substrates (100–200-μm thickness) in order to avoid the excitation of substrate modes. Furthermore, via-holes usually are necessary in order to realize connection with the ground metallization. Coplanar circuit design allows one to use substrates of normal thickness and requires no via-holes. However, air-bridges are necessary to connect the parts of the metallization. Especially in the case of monolithic integration of antenna structures, the microstrip concept is advantageous, since due to the thinned substrates, surface-wave excitation may be avoided.

1) Microstrip Lines: Microstrip lines are most commonly used in monolithic integrated circuits. Due to the back metallization, the substrate can easily be fixed on a metallic mount providing an efficient heat sink. Mounting of lumped elements in series configuration is very easy. Mounting of lumped elements in shunt configuration and fabrication of shorts requires via holes, which in monolithic integrated circuits are technologically expensive.

The maximum frequency of operation with a microstrip is mainly limited by the excitation of spurious modes, namely higher order hybrid microstrip modes, trapped surface waves, and radiating waves. The cutoff frequency $f_{c,HE1}$ of the first-order hybrid microstrip mode is given by [57]

$$f_{c,HE1} \doteq \frac{c_0 Z_0}{2\eta_0 h} \tag{11}$$

where Z_0 is the characteristic impedance of the microstrip line, c_0 is the free-space light velocity, and $\eta_0 = 377\,\Omega$ is the characteristic impedance of free space. A $Z_0 = 50$-Ω microstrip line on a $h = 100$-μm-thick silicon substrate with 80-μm width (11) yields a cutoff frequency $f_{c,HE1} \doteq 200$ GHz.

2) Coplanar Lines and Coplanar Strip Lines: Coplanar lines have been investigated theoretically and experimentally [60], [61], and particularly with respect to applications in hybrid and monolithic integrated circuits [62]–[66]. They substantially extend the flexibility in the circuit design and exhibit some distinctive advantages. Mounting of components in shunt and series configuration is equally easy and no via holes are needed. The fundamental mode propagating along coplanar lines at low frequencies is quasi-TE. With increasing frequency the fields and surface currents concentrate around the slots, and finally the quasi-TE slot-line mode occurs. The coplanar stripline is due to its balanced nature, ideally suited as a feed line for printed dipole antennas [67]. Passive elements for coplanar MMIC's are reported in [34].

3) Slot Lines: The slot line is a balanced transmission line. In general, due to the hybrid nature of the fundamental mode, treatment of the slot line requires a full-wave analysis. For transverse dimensions below the wavelength, the structure supports a quasi-TEM type of mode similar to that of the coplanar stripline [68]. The slot line finds interesting applications as resonators [52] and resonant antennas [69]–[71]. However, slot lines suffer from high dispersion, high radiation loss, and low power-handling capabilities. The fundamental mode of the slot line is a quasi-TE mode.

B. Transmission-Line Discontinuities

For a variety of stripline and microstrip-line discontinuities, equivalent circuits and closed-form expressions for the reactances have been found [72], [73].

In [74] and [75] open circuits, short circuits, step changes in width, and T-junctions of coplanar waveguides have been investigated. In [76]–[79], simple models for coplanar stubs T-junctions were developed. Radiation losses of short-circuited coplanar waveguides have been investigated in [80]. At coplanar-waveguide discontinuities substantial mode conversion can occur [64], [77].

Planar resonators are open structures and suffer from energy leakage into radiating and surface-wave modes. This radiation can be utilized if the resonator is also used as an antenna. The rectangular planar resonator consists of a planar transmission line of length l. For an open microstrip resonator, resonance occurs for

$$l + 2\Delta l = n\frac{\lambda_g}{2}, \qquad n = 1, 2, 3, \cdots \tag{12}$$

with the guide wavelength λ_g and the length extension Δl of the open microstrip line.

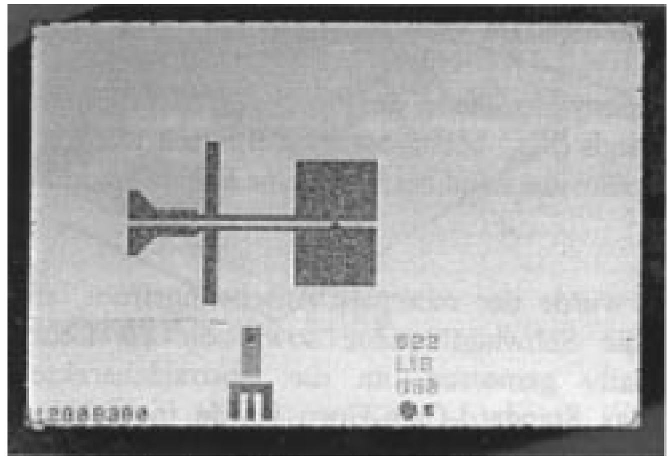

Fig. 10. 76-GHz patch antenna.

C. Planar Antennas

In the millimeter-wave region with small antenna dimensions, a considerable antenna gain may be achieved. This allows one to include planar antenna structures into SIMMWIC's. An overview of planar antennas is presented in [81] and [82]. Using integrated antennas as the radiating structures, feed lines and associated components such as oscillators, detectors, and mixers may be combined. Planar antennas with 36 and 96 elements have been designed and fabricated [4], [83]. In this section, we discuss basic design concepts of planar millimeter-wave antennas. For a comprehensive review of millimeter-wave antennas in general, we refer to [84]–[87]. The design of planar antenna arrays in the millimeter-wave region involves new problems, since substrate surface waves may increase mutual coupling between the antenna elements, and losses in the feed lines limit the array size. However, in order to minimize the SIMMWIC chip size, the combination of a single patch or slot antenna element on the chip with mirrors or dielectric lenses may be preferable.

1) Patch Antennas: The microstrip patch is the most commonly used planar millimeter-wave antenna and the basic antenna element for antenna arrays. The application of these antennas, however, is limited by their narrow bandwidth. At millimeter-wave frequencies, they suffer from excitation of surface-wave modes and from losses in the feed lines. Excitation of surface-wave modes results in poor radiation efficiency and in mutual coupling of antenna elements in antenna arrays.

Fig. 10 shows a 76-GHz patch antenna. The magnitude of the 2-D surface current distribution at 76 GHz is depicted in Fig. 11. Resistance, reactance, and radiation efficiency as a function of the frequency are shown in Fig. 12 [88]–[90].

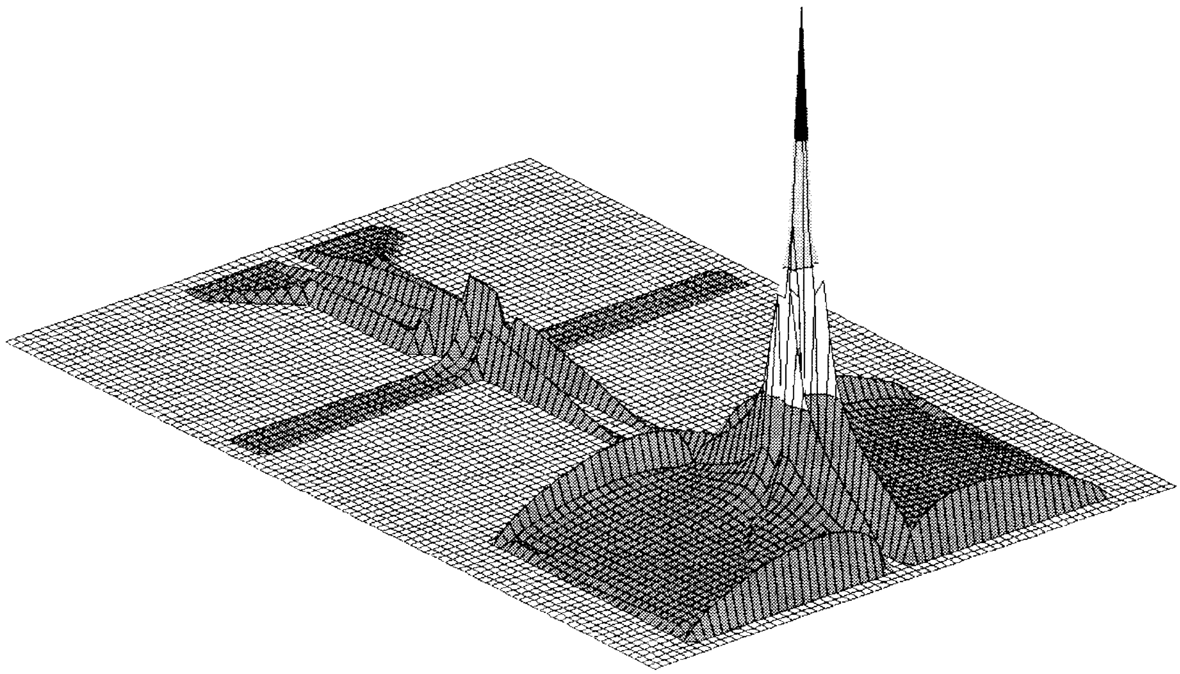

Fig. 11. Patch antenna: surface current distribution at 76 GHz.

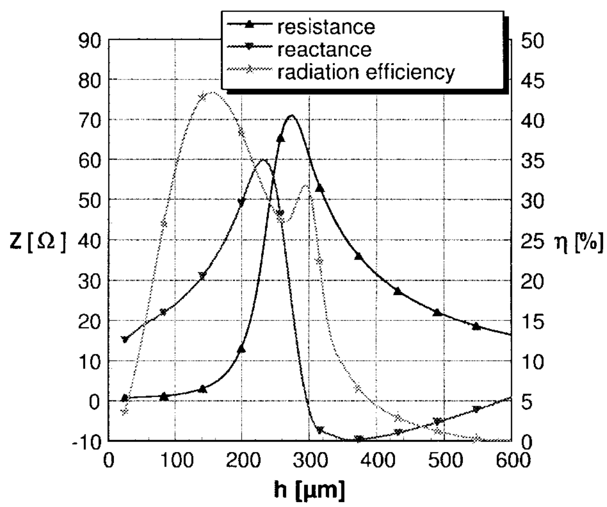

Fig. 12. Impedance and radiation efficiency.

As a very interesting result, we obtain maximum radiation efficiency for a substrate height of 125 μm. The diode feeding the patch antenna is located at the point of the highest surface current density—the junction between the patches—resulting in a minimal resistance of only 2.1 Ω. A three-dimensional (3-D) experimental analysis of the near- and far-field radiation of planar millimeter-wave antennas has been provided by Pfeifer *et al.* [91] using electrooptic testing and nearfield probing.

2) Slot Antennas: Compared with patch antennas, slot antennas exhibit a higher bandwidth. The slot length equals one line wavelength. Coplanar active devices can be placed within the radiating aperture and the slot simultaneously acts as a resonator. In [92] and [93], results of a rigorous full-wave analysis of half-wavelength and full-wavelength slot antennas are reported. A slot antenna on a monolithically integrated

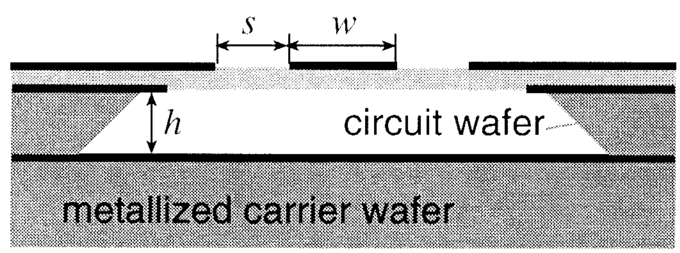

Fig. 13. Cross section of the microshield line.

cavity resonator exhibits a very large radiation efficiency of about 50% [94], [95].

D. Micromachined Circuits

Besides their advantages of high design flexibility, reduced area, and simple integration with active devices, planar circuits suffer from undesirable electromagnetic effects and parasitics limiting their electrical performance. These frequency-dependent parasitic effects are due to the losses in the conductors and in the dielectric material as well as the radiation losses of the open planar structures. The radiation effects may be reduced by sophisticated packaging techniques. A very promising attempt to overcome the drawbacks of planar circuits are the microshield line concept and the suspended membrane microstrip (SMM) line concept [96]–[100]. The advantages of the microshield line and SMM's are low dielectric losses and low radiation losses at discontinuities. Both transmission-line types are fabricated by micromachining techniques on an SiO_2–Si_3N_4–SiO_2 membrane, grown on a silicon substrate. Fig. 13 shows the cross section of a microshield line. The membrane thickness is 1.5 μm. Standard lithographic and processing techniques are used for the metal pattern definition and cavity etching. The depth of the ground plane cavity is controlled by timing the etch. The microshield line has properties similar to a coplanar line without dielectric support. In coplanar waveguides, the radiation loss into parasitic modes is a function of both f^3 and $(\epsilon_r - 1)^2$ where f is the frequency and ϵ_r is the relative permittivity of the substrate [82], [101]. Therefore, although radiation loss is increasing strongly with frequency, it may be eliminated completely by removing the dielectric. At 35 GHz, losses as low as 0.03 dB/mm have already been measured [102].

Micromachined techniques already have been applied to the development of circuits. Stripline resonators on thin dielectric membranes exhibited dispersion-free conductor-loss limited performance at 13.5, 27.3, and 39.6 GHz [103]. The fabrication of microshield filters at 30 and 90 GHz, microstrip bandpass filters at 94 GHz, and a 250-GHz bandpass filter with 1.0–1.5-dB insertion loss has been reported [102].

The fabrication of micromachined circuits requires a higher technological effort than the fabrication of planar circuits. However, since micromachined circuits can be self-packaged, it may be cost-competitive with packaged planar circuits.

V. Monolithic Integrated Circuits

A. Amplifiers

A monolithic SiGe HBT Ka-band amplifier has been reported in [35]. Its design is based on coplanar structures. Slot-line modes are suppressed by air bridges. As the passive circuit elements coplanar lines, metal–insulator–metal (MIM) capacitors and spiral inductors were used. The amplifier exhibits a gain of 4 dB in the frequency range from 20 to 24 GHz.

B. Oscillators

Monolithic integrated HBT oscillators exhibit a considerably lower phase noise and a higher frequency stability than monolithic IMPATT oscillators. However, currently they can only be realized for frequencies up to approximately 40 GHz [104]–[106]. The coplanar 25.5-GHz SiGe HBT oscillator chip is depicted in the lower part of the module shown in Fig. 20. A monolithic integrated SiGe HBT oscillator with 2-dBm output power at 38 GHz has been fabricated in coplanar technology on high-resistivity silicon substrate [106].

As active elements for planar millimeter-wave oscillators, IMPATT diodes yield high continuous-wave (CW) output power at frequencies up to above 100 GHz. In order to obtain both high output power and a narrow spectrum, IMPATT diodes must be connected with a low-impedance series resonant circuit. Since for planar resonators the quality factors that can be achieved typically range below 100, one must take care in order to obtain a low-impedance planar resonator design. Best results were obtained using a planar circular-disk resonator with the IMPATT diode in the center and a through contact beyond the IMPATT diode to the circuit ground plane. Based upon optimized circuit layouts, CW power output values as high as 20 mW at 93 GHz [83], 200 mW at 73 GHz, and 100 mW at 140 GHz [107] were achieved. Fig. 14 shows the 140-GHz oscillator. The planar resonant structure consists of a disc resonator with diameters of 400–500 μm. The substrate thickness is 70 μm. The via-hole in the center of the disc resonator is realized by using micromachining techniques. A DLHL IMPATT diode is used in this circuit. At the oscillation frequency of 147 GHz in continuous-wave operation, 100-mW output power at an efficiency of 4.5% was achieved.

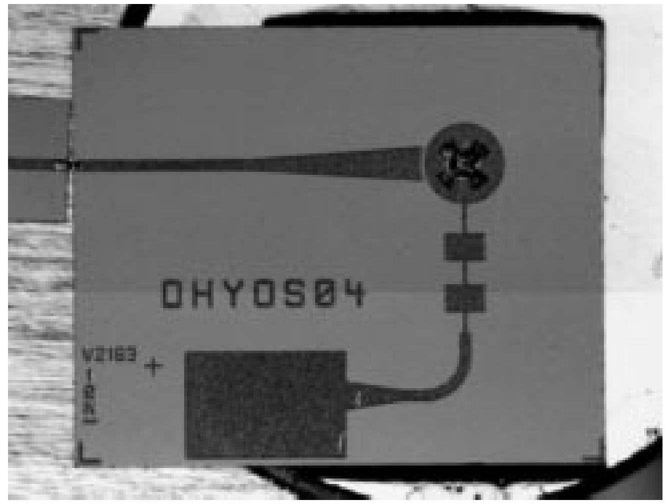

Fig. 14. Planar 100-mW D-band IMPATT oscillator.

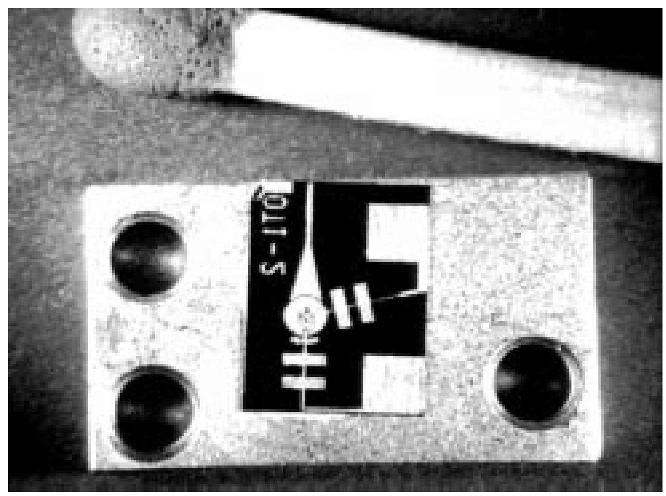

Fig. 15. Voltage-controlled IMPATT oscillator.

A fully monolithic integrated planar-disc resonator oscillator with an output power of 1.8 mW at 61 GHz has already been reported [108]. The IMPATT diode is located at the side of the substrate with the ground metallization. The diode is connected to the disc metallization via an etched and metallized conical hole.

Many applications of millimeter-wave oscillators require electronic frequency tuning. Fig. 15 shows a varactor-diode tunable planar IMPATT oscillator [109]. The oscillator output power is 18 mW at 80.2 GHz. The tuning range is 425 MHz.

Using coplanar IMPATT diodes, no via holes are required. Several coplanar oscillator designs have already been discussed [51], [52]. In the slot-line oscillator, the coplanar IMPATT diode is connected to the center of a slot line [52]. The oscillator was fabricated on a 100-μm substrate in

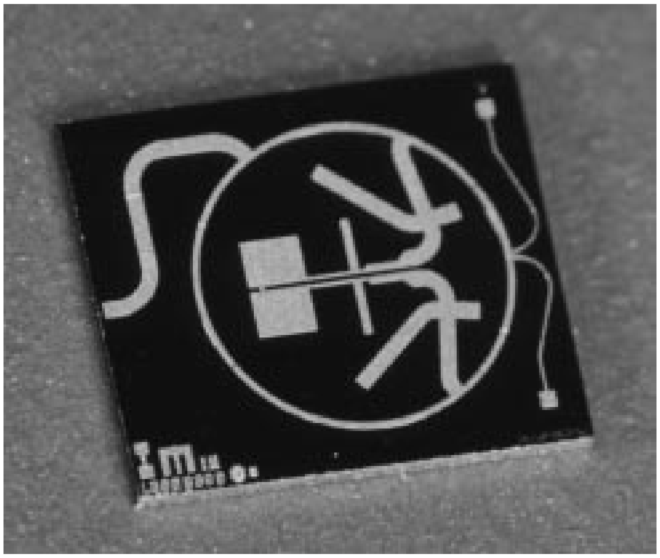

Fig. 16. Front-end with planar antenna.

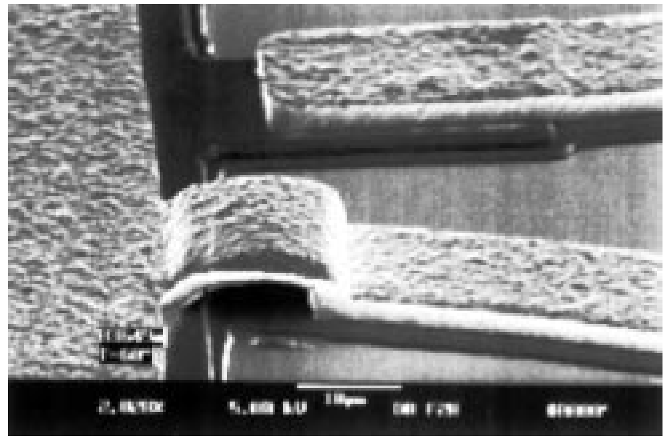

Fig. 17. MIM capacitor with bias lines.

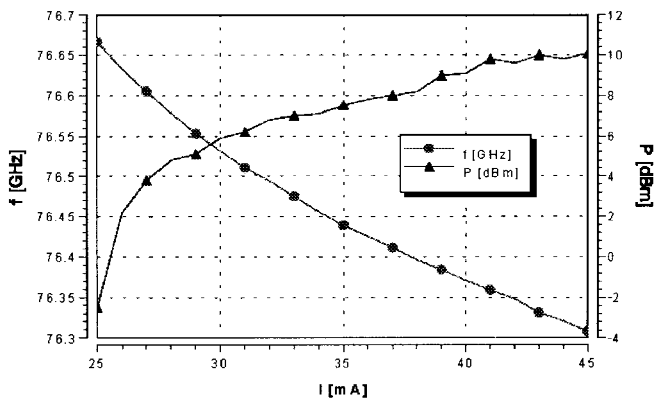

Fig. 18. Oscillation frequency and radiated power.

order to minimize the surface wave losses. The slot length is 1.12 mm and the slot width is 80 μm. The IMPATT diode diameter is 20 μm. A radiated output power of 7 mW was measured at 109 GHz. With dual-fed coplanar resonators, very low radiation losses are achieved. In this configuration, at each end of a $\lambda/2$ coplanar line resonator, an IMPATT diode is integrated. The generated power is delivered to another coplanar line, which is capacitively coupled at the center of the resonator [110].

The required frequency stabilization is achieved by means of subharmonic injection locking [111]. The design of planar IMPATT oscillators is very sensitive with respect to the matching of the IMPATT diode to the planar resonator–antenna structure.

C. Transmitter Modules

In its minimal configuration, a SIMMWIC transmitter consists of an oscillator coupled to planar antenna. It is advantageous to combine oscillator and antenna by using the antenna structure also as the resonator of the oscillator. This facilitates not only a small circuit layout, but also avoids losses between oscillator and antenna [112], [113]. This type of oscillator is commonly called an active integrated antenna. An integrated transmitter for automotive applications delivered a radiated power of 1 mW at 79 GHz [114]. The distance to be covered is limited by the coherence length of the free-running IMPATT oscillators [115]. An excellent carrier-to-noise ratio of 81.7 dBc/Hz at an offset of 100 kHz has been achieved. Fundamental or subharmonic injection locking using an HBT oscillator improves the coherence length of the transmitter [111].

Fig. 16 shows a 76.5-GHz front-end SIMMWIC with a planar antenna, coplanar IMPATT diode, and matching circuit [116], [113]. The SIMMWIC exhibits an area of 2.6 mm $\times$ 3.2 mm. The planar antenna is formed by the two rectangular patches in the center of the circuit. The coplanar IMPATT diode is inserted in the narrow bridge connecting the two antenna patches. The bridge between the two antenna patches is located at the spots of maximum current density in the two patches. This yields a low impedance termination of the IMPATT diode for maximum RF output power. The ring surrounding the structure forms a rat-race coupler and also serves as balun transformer for the synchronization signal feeded into the circuit via the stripline coming from the left. The synchronization signal at the subharmonic frequency 25.5 GHz is supplied via the broad microstrip line on the left side of the chip. The two narrow striplines on the right side of the chip serve as the dc bias lines. The dc isolation in the hybrid ring is performed via two MIM capacitors inserted in the ring. Fig. 17 shows a detail of the MIM capacitor with the upper bias line connected with the bottom metallization and the lower bias line connected with the top metallization of the MIM capacitor. Fig. 18 shows the dependence of the oscillation frequency f and the radiated power on the IMPATT diode bias current I.

Fig. 19 shows the block circuit diagram of a millimeter-wave radar sensor [116]. The system consists of a 25.5-GHz HBT oscillator [105], 76.5-GHz front-end, and signal-processing unit. The millimeter-wave signal generated by the IMPATT oscillator is radiated by the antenna. The signal reflected by an object to be detected is received again by the antenna. The IMPATT oscillator also acts as the self-oscillating mixer for the received signal.

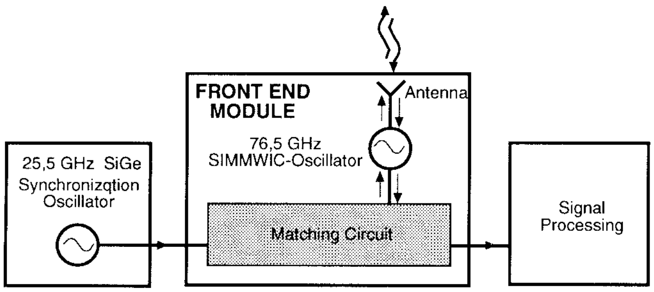

Fig. 19. Circuit diagram of the millimeter-wave sensor.

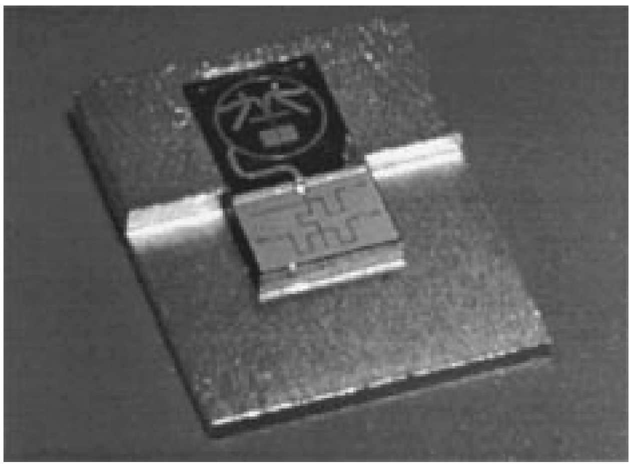

Fig. 20. Miniature radar module.

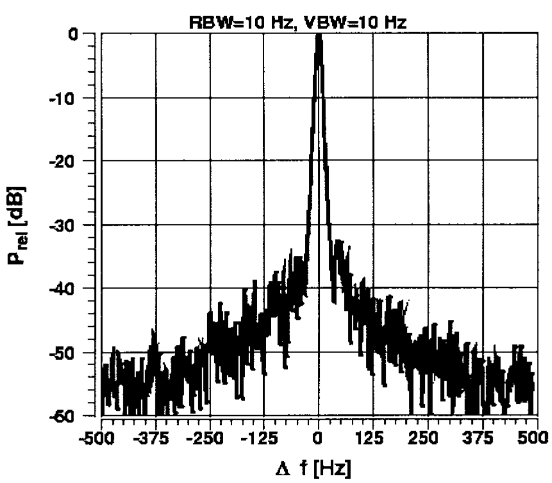

Fig. 21. Power spectrum.

The RF module with the 25.5-GHz HBT synchronization oscillator chip and the 76.5-GHz front-end chip is depicted in Fig. 20. Fig. 21 shows the power spectrum emitted from the synchronized radar module.

D. Receiver Circuits

Already in the basic SIMMWIC concept [83], [117], a transmission link with transmit and receive modules was considered. As a key element of the receiver module, the Schottky diode was developed. A 93-GHz SIMMWIC receiver with a planar 36-element antenna and a Schottky diode has

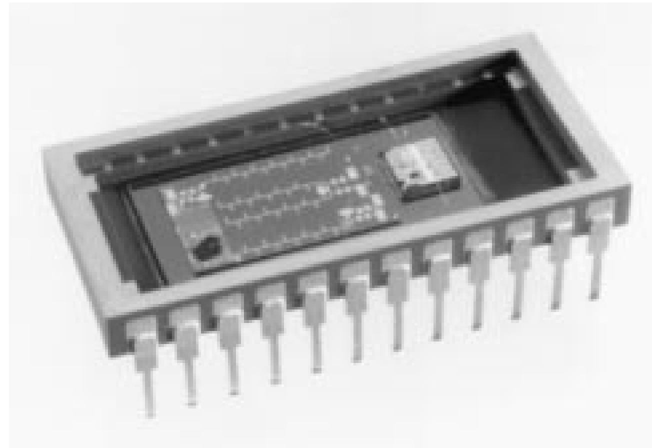

Fig. 22. Rectenna module.

been realized. Kasper has proposed the name "rectenna" for a monolithic integrated circuit containing a planar antenna and rectifying Schottky diodes [118]. The receiver has been integrated monolithically on a highly insulating silicon substrate. The antenna dimensions are 5.4 $\times$ 5.6 mm^2. The Schottky diode exhibits 4-Ω series resistance and a junction capacity of 0.1 pF. The measured receiver sensitivity is 65 V/Wcm^{-2}.

A monolithic integrated silicon rectenna has been developed by Kasper *et al*. [118]. The rectenna is fabricated on an 100-μm-thick silicon substrate and is realized in stripline technology. The linear antenna structures are formed by $\lambda/2$ patches in $\lambda/2$ distance. Fig. 22 shows a hybrid circuit containing the rectenna chip and a baseband amplifier in CMOS technology. The rectenna exhibits a center frequency of 94.6 GHz and a bandwidth of 1.6 GHz. The CMOS amplifier has a 32-dB gain. The sensitivity of the rectenna with amplifier is 1600 V/Wcm^{-2}.

Thieme *et al*. have developed a monolithic integrated circularly polarized W-band direct detection receiver for six-port polarimetric radar systems [119]. The dual-patch-antenna direct-detection receiver, shown in Fig. 23, contains two asymmetrically fed antenna patches of dimensions 500 μm $\times$ 550 μm. Phase quadrature is achieved by directly exciting two slightly detuned fundamental modes TM01 and TM10. A cross polarization discrimination of 14 dB has been measured at 76 GHz.

E. Mixer Circuits

A monolithic integrated coplanar millimeter-wave Schottky diode mixer has been realized in SIMMWIC technology [54]. Fig. 24 shows the single balanced-mixer circuit. The branch line coupler on the left side of the circuit forms the two 180° phase-shifted signals. At 77 GHz, a conversion loss of 7.8 dB has been measured for an RF power of -10 dBm, and an LO power of 6 dBm. The intermediate frequency is 1 GHz.

F. Digital Circuits

Digital circuits cannot be realized in conventional SIMMWIC technology since the insulation of the transistors requires low-resistivity substrates. However, initial successful

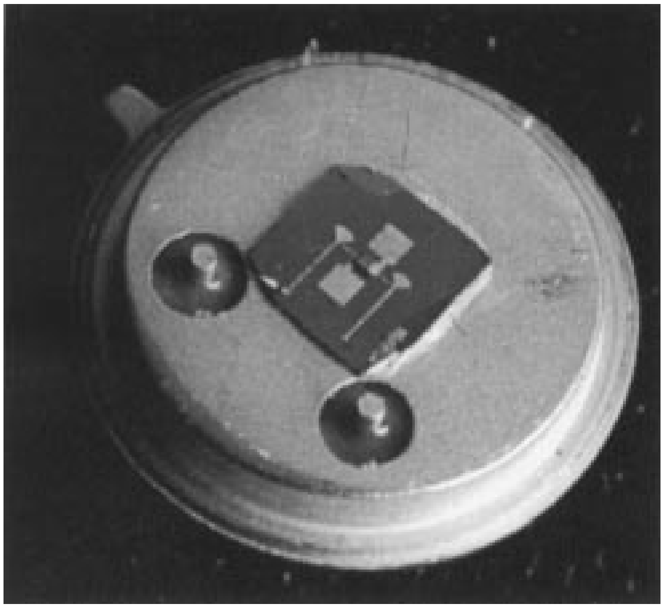

Fig. 23. Dual-patch-antenna receiver.

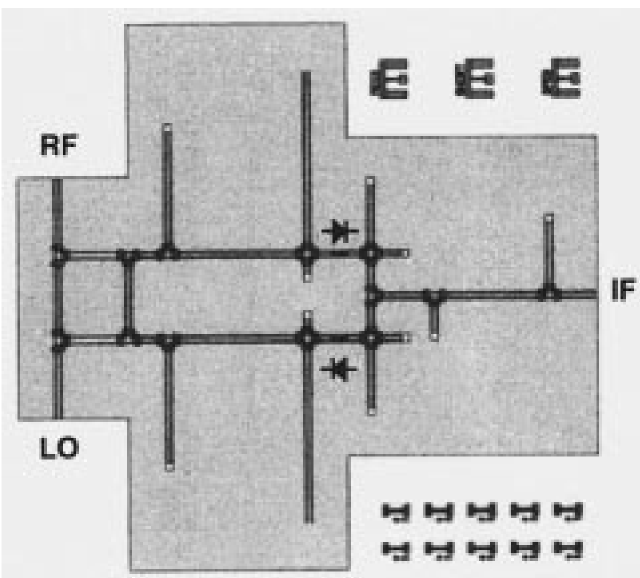

Fig. 24. Coplanar mixer with silicon Schottky diodes.

attempts have already been made to combine SIMMWIC technology and CMOS technology [12]. A major challenge for the future silicon technology may be to combine SIMMWIC technology with bipolar high-speed emitter-coupled logic (ECL) digital technology. For digital high-speed circuits, Si bipolar transistors as well as SiGe-base HBT's are of interest. Meister *et al*. have described an epitaxial SiGe-base HBT technology suitable for analog as well as digital applications [37]. Up to now, Si- and SiGe-based high-speed digital circuits have been realized for toggle frequencies up to 50 GHz [16], [17], [120], [121]. Based on a CMOS compatible 0.5-μm silicon bipolar technology, gate delay times of 16 ps and static frequency divider operation up to 35 GHz has been achieved [16], [17]. A 60-Gb/s time-division multiplexer has been realized in SiGe bipolar technology [120].

A future Si/SiGe heterostructure CMOS technology may take advantage of the high carrier mobility also in p-channel devices. Simulations of Si/SiGe heterostructure CMOS logic circuits exhibited gate delay times as low as 2.5 and 0.5 ps/stage at a power supply of 1 and 2.5 V, respectively, [45]. Large-signal measurements of Si/SiGe heterostructure field-effect transistor inverter circuits yielded delay times down to 25 ps [122].

VI. Applications and Outlook

SIMMWIC's applications in millimeter-wave sensorics and communications have already been investigated [114], [115], [116], [123]. Complete receivers and transmitters may be integrated monolithically using IMPATT diodes, SiGe HBT's, p-i-n diodes, and Schottky diodes. The advantages of millimeter waves are high bandwidth for communication applications, high resolution for sensor applications, and high antenna gain even with small antennas. The future availability of low-cost millimeter-wave components and millimeter-wave monolithic integrated circuits (MMIC's) will stimulate the penetration of millimeter-wave technology into commercial and consumer electronics [124].

Combining millimeter-wave analog circuits with digital signal-processing circuits on a single chip may provide cost-effective solutions for single-chip receivers, transmitters, and millimeter-wave sensors. First attempts to combine SIMMWIC technology with CMOS technology have already been made [12]. However, SIMMWIC technology with standard bipolar, CMOS, and BICMOS technology may also be hampered in the future due to different substrate requirements and processing technologies. In this case, multichip module technology may be an interesting alternative to a completely monolithic integration [125].

A very interesting field of future millimeter-wave communication applications of SIMMWIC's is the broad-band short-range and in-house communication. Compared with optical systems, millimeter-wave communication systems have superior transmission properties in the case of adverse weather conditions or in industrial environments with dust, smoke, or dirt. Compared with microwave systems, the very small dimensions of millimeter-wave systems are advantageous. Concerning the dimensions, millimeter-wave communication and sensor systems are competitive with optical systems.

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