SILICON MILLIMETER–WAVE CIRCUITS FOR RECEIVERS AND TRANSMITTERS

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ABSTRACT

For the 90 GHz band we have fabricated a monolithic integrated Schottky diode receiver on a highly insulating silicon substrate. The receiver consists of the monolithic Schottky diode and a planar antenna structure on one silicon chip. The receiver sensitivity is 65 μWcm^{-2}. The receiver antenna half–power beamwidth is 23° and the side lobe attenuation is 12 dB. Also new results on planar W–band oscillators hybrid integrated on highly insulating silicon substrates with double drift region IMPATT diodes are presented. The CW oscillator output power is greater than 20 mW and the efficiency is more than 1 percent.

INTRODUCTION

Theoretical and experimental investigations already have shown the excellent feasability of highly insulating silicon as the substrate material for MMICs in the 90 GHz region [1,2]. Such silicon MMICs will be of interest for single chip millimeter wave transmitters and receivers for small distance links and for sensor applications.

THE RECEIVER

The receiver consists of the antenna structure coupled via a microstrip line to the monolithic silicon Schottky diode. The Schottky diode is terminated by a $\lambda/4$ microstrip line. Two DC–networks for biasing and for coupling out the received signal are connected with the microstrip lines. The antenna structure consists of 36 radiating elements on an area of 5.4· 5.6 mm^2, where the weights of the elements were calculated after Dolph–Chebyshev. To achieve uniform phase distribution the discontinuities were taken into account using the network analysis program SANA [3]. The photography of the receiver is shown in Fig. 1.

A planar Schottky diode was fabricated on high resistivity silicon. Fig. 2 shows the active layers of the diode. The n$^+$–buried layer was made by a diffusion process using As spin on glass. The thin (0.1 – 0.2 μm) active n–layer of the Schottky diode was grown by silicon molecular beam epitaxy (Si–MBE). The Schottky contact was made by a lift off process using titanium as Schottky metal. The ohmic contact was formed by Ti/Pt/Au. Fig. 3 shows a scanning electron micrograph of a fabricated planar Schottky diode. Preliminary experimental results are: 3 μm Schottky contact width, series resistance of 25 Ω down to 4 Ω, junction capacitance around 0.1 pF and an ideality factor of approximately 1.1. Using Titanium as Schottky contact material a barrier height of 0.5 V was obtained. With this Schottky diode a monolithic integrated receiver containing a planar antenna structure was fabricated on one single high resistivity silicon substrate.

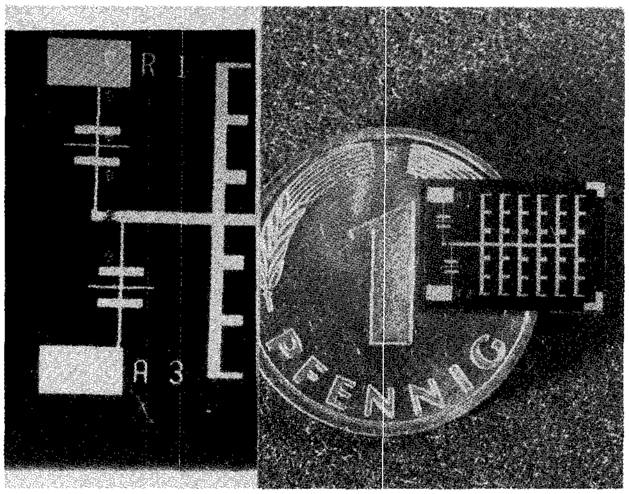

Fig. 1: Photos of the monolithic integrated receiver

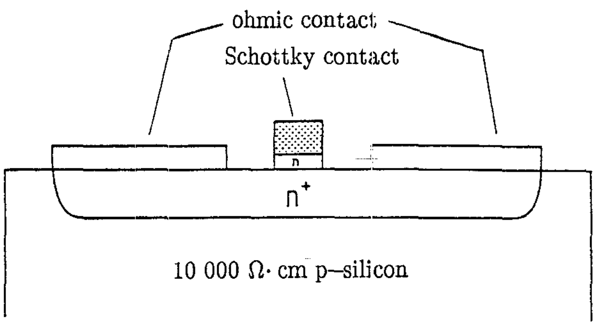

Fig. 2: Active layers of the Schottky diode

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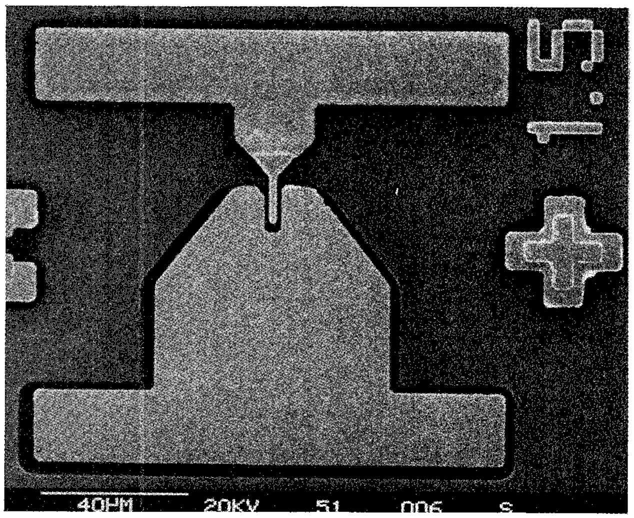

Fig. 3: Scanning electron micrograph of a fabricated planar Schottky diode

The properties of the antenna, the Schottky diode and the complete receiver have been investigated experimentally. Fig. 4 shows the measured detector voltage versus the power density. The measured radiation pattern of the antenna is depicted in Fig. 5. The side lobe attenuation is 12 dB and the half–power beamwidth is 23°. Using the receiver cicuit to detect radiation at 93 GHz the Schottky diode was biased with 270 mV. A preliminary experimental result for the receiver sensitivity is 65 μWcm^{-2}.

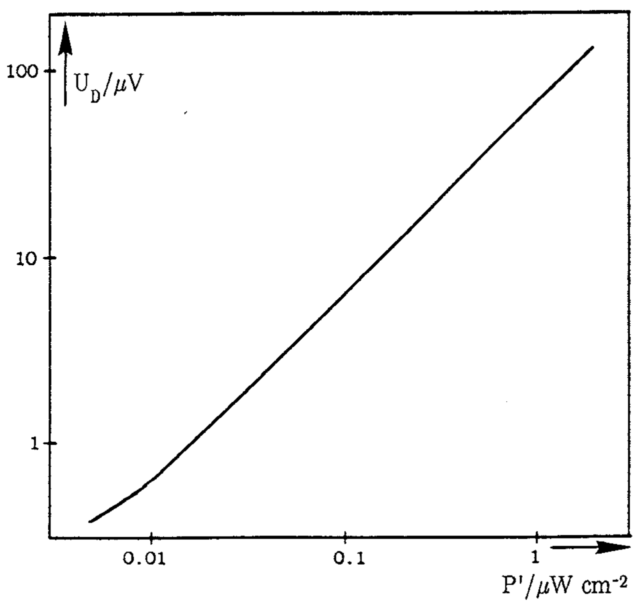

Fig. 4: Measured detector voltage versus power density

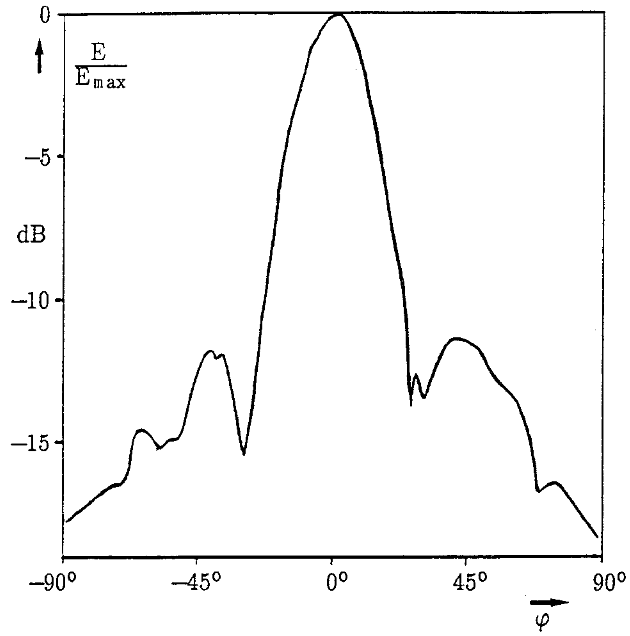

Fig. 5: E–plane radiation pattern of the receiver antenna

THE OSCILLATOR

We have also fabricated planar hybrid integrated oscillators on highly insulating silicon substrates. The planar circuit configuration has already been described in [1]. The disk resonator can be considered as a lossy radial waveguide loaded with a radiating resistance, a fringing field capacitance and the external load formed by the directly coupled tapered microstrip line. Fig. 6 shows the equivalent circuit of the loaded radial line.

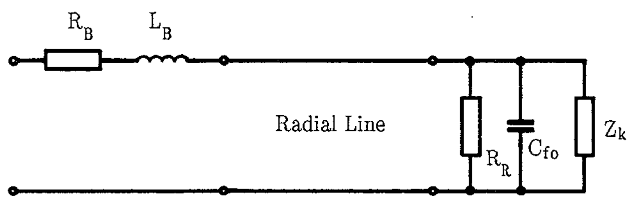

Fig. 6: Equivalent circuit of the resonator
$R_B = 0.05\ \Omega$; $L_B = 4$ pH; $C_{fo} = 0.26$ pF

The input impedance Z_i at a radius r of a radial line with the height h and the outer radius r_o is given by

$$Z_i(r) = \frac{U(r)}{I(r)} = Z_{RL}(r) \frac{\mathcal{A}\ Z_o + j\,\mathcal{B}\ Z_{RL}(r_o)}{\mathcal{D}\ Z_{RL}(r_o) + j\,\mathcal{C}\ Z_o}$$

with

$$\mathcal{A}(\kappa r,\kappa r_0) = N_0(\kappa r)J_1(\kappa r_0)-J_0(\kappa r)N_1(\kappa r_0)$$

$$\mathcal{B}(\kappa r,\kappa r_0) = J_0(\kappa r)N_0(\kappa r_0)-N_0(\kappa r)J_0(\kappa r_0)$$

$$\mathcal{C}(\kappa r,\kappa r_0) = J_1(\kappa r)N_1(\kappa r_0)-N_1(\kappa r)J_1(\kappa r_0)$$

$$\mathcal{D}(\kappa r,\kappa r_0) = J_1(\kappa r)N_0(\kappa r_0)-N_1(\kappa r)J_0(\kappa r_0) \quad ,$$

the characteristic impedance

$$Z_{RL}(r) = Z_F \frac{h}{2\pi r}$$

and the load impedance

$$Z_0(r_0) = U(r_0)/I(r_0) \quad .$$

J_n and N_n are the Bessel functions of the first and second kind. Z_F is the intrinsic impedance of the silicon and κ is the complex wave number given by

$$\kappa^2 = \omega\varepsilon'(\omega\mu_0 - \frac{R_A}{h}\tan\delta) - j\omega\varepsilon'(\frac{R_A}{h} + \omega\mu_0 \tan\delta)$$

with the surface resistance R_A and the loss tangent $\tan\delta$, which is $1.3 \cdot 10^{-3}$ [1]. The radiation resistance R_R is given by [2]

$$R_R = \frac{6 \; Z_{F0}}{(k_0 r_0)^4 \;\; \pi \; F(k_0 r_0)}$$

where Z_{F0} and k_0 are the intrinsic impedance and the wave number of free space and

$$F(k_0 r_0) = \frac{3}{(k_0 r_0)^2} \int_0^{\pi} J_1^2(k_0 r_0 \sin\vartheta) \sin\vartheta \, d\vartheta$$

The fringing field capacitance is 0.25 pF [3]. The impedance of the bond stripes and the external load formed by the directly coupled tapered microstrip line were taken into account. The resulting input impedance versus the frequency is shown in Fig. 7. In the neighborhood of minimum of the real part of the resonator input impedance the imaginary part of the impedance is positive, and the matching condition for the IMPATT diode is fulfilled.

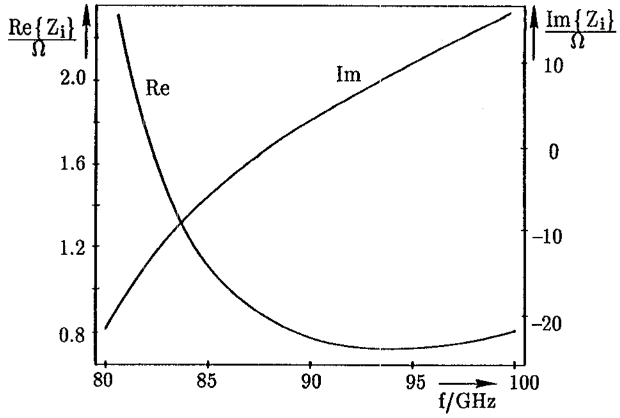

Fig. 7: Input impedance of the radial line resonator

We have fabricated the planar hybrid integrated oscillators on 10000 Ω·cm silicon substrates employing Quasi Read Double Drift IMPATT diodes made by silicon molecular beam epitaxy [5]. The planar oscillator circuit consists of a disk resonator, a tapered transmission line coupled directly to the disk resonator, and a dc bias network. The thickness of the silicon substrate is 190 μm and the chip size is $6 \cdot 4.5$ mm^2.

The silicon substrate was covered by a 100 nm thick thermal oxide. The gold microstrip lines were evaporated, conventionally defined by photolithography and selectively electroplated for a thickness of 3 μm. The IMPATT diode with a diameter of 32 μm is mounted in the center hole of the disk resonator and bonded to the resonator via four bond stripes. Fig. 8 shows a photo of the oscillator.

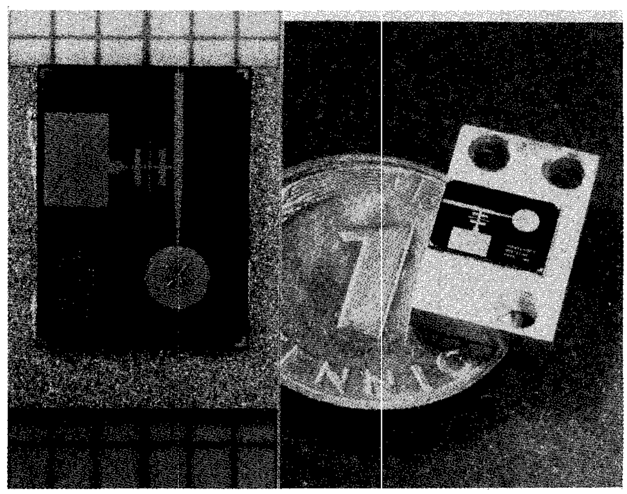

Fig. 8: Photos of the planar oscillator

With these oscillators we achieve more than 20 mW CW output power in the W–band with efficiencies in excess of 1%. Fig. 9 shows a P–J characteristics of a 30 mW oscillator. The low threshold current density proves the low series resistance and the achieved impedance matching. The typical increase of output power with increasing current density is interrupted at J = 15 kA cm^{-2} presumably because of bias oscillations.

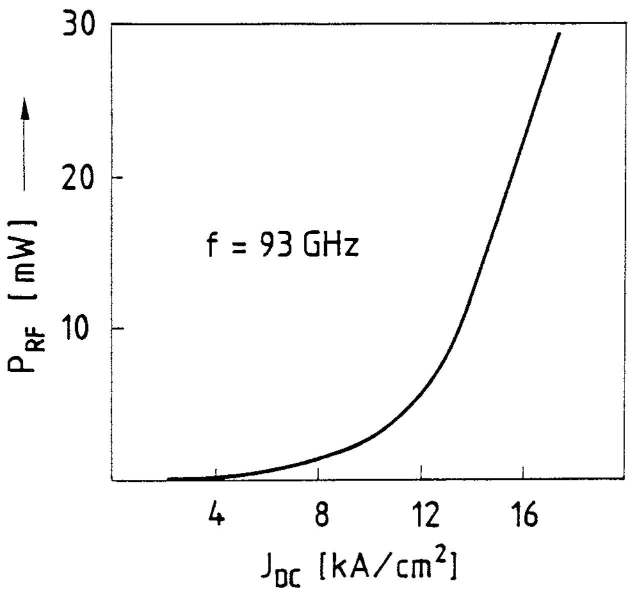

Fig. 9: P–J characteristic of a planar oscillator

CONCLUSIONS

A W–band monolithic integrated receiver was fabricated on highly insulating silicon. For different applications different radiation characteristics can be obtained depending on the antenna strucure. So a wide range of applications will be possible. The fabricated hybrid integrated IMPATT oscillators show good characteristics for low current densities. However, for higher current densities bias oscillations occur and the microwave power nearly vanishes. So the oscillator structure will be investigated to avoid bias oscillations.

Acknowledgment

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