Silicon High-Resistivity-Substrate Millimeter-Wave Technology

JOSEF BUECHLER, ERICH KASPER, PETER RUSSER, SENIOR MEMBER, IEEE, AND KARL M. STROHM

Abstract **—The application of molecular beam epitaxy (MBE) and X-ray lithography for the fabrication of monolithic integrated millimeter-wave devices on high-resistivity silicon has been investigated. Process compatibility and the retention of high-resistivity characteristics were measured using the spreading resistance method and Hall measurements after various process steps. Microstrip resonators of ring and linear geometry were fabricated on 10 000 Ω·cm silicon substrates. For linear microstrip resonators, the attenuation was found to be less than 0.6 dB/cm at 90 GHz. A 95-GHz IMPATT oscillator circuit and a planar microstrip antenna array have been fabricated on highly insulating silicon substrates. For the oscillator, a combined monolithic–hybrid integration technique was used to attach the discrete IMPATT diode to the resonator circuit. The oscillator does not require tuning elements. Preliminary experimental results are 8 mW of output power with 0.2 percent efficiency at 95 GHz.**

I. Introduction

HIGHLY INSULATING SILICON is very promising as the substrate material for future applications in planar millimeter-wave circuits [1]. These circuits may be monolithic integrated as well as hybrid–monolithic integrated. The basic geometric structure for planar millimeter-wave circuits is the microstrip line. Fig. 1 shows the calculated attenuation coefficient dependence on the line width w for a microstrip line on a 7000-Ω·cm silicon substrate material at 90 GHz with a constant w/h ratio of 0.8. The attenuation contributions of the substrate, of the conductor strip, and of the ground plane are specified. For frequencies above 40 GHz and a resistivity of the substrate material greater than 2000 Ω·cm, the dominant loss mechanism is the skin effect in the conductors. Therefore, the use of highly insulating silicon as the dielectric of planar circuits will not degrade the circuit performance. Of special interest is the frequency band from 90 GHz to 110 GHz, where the integration of complete transmitters or receivers, including antenna structures, is possible. The problems involving silicon are that it must be highly resistive and that this high resistivity should be preserved during various processing steps. During the first investigation on silicon for monolithic microwave integrated circuits, it was found that silicon undergoes resistivity changes during high-temperature processing steps and that the

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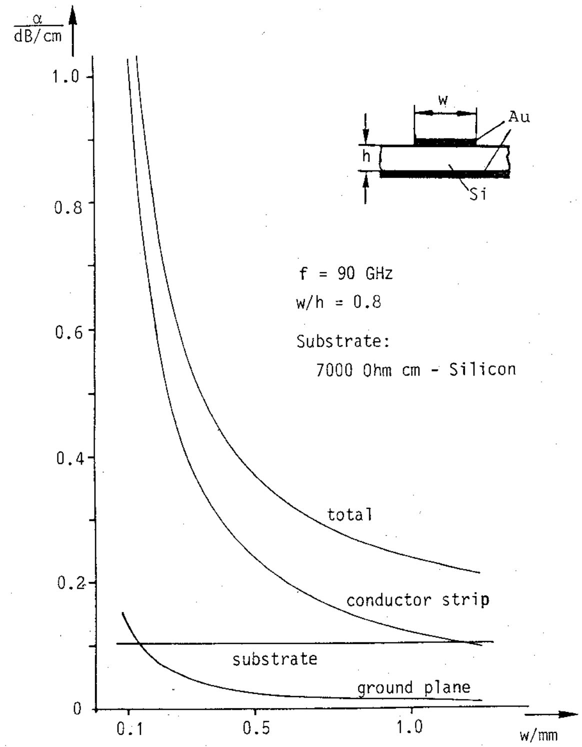

Fig. 1. Calculated attenuation coefficient of microstrip lines on silicon substrate.

attenuation for microstrip lines increased to intolerable values [2]. Generally, it was believed that the processing temperatures must not exceed 800°C. This was fulfilled by a group at RCA using ion implantation and laser annealing [3].

Modern techniques such as molecular beam epitaxy (MBE) for the growth of active, monocrystalline films with abrupt junctions at moderate temperatures (550°–750°C) [4] and X-ray lithography for lateral patterning of submicron lines [5] are promising technologies for the monolithic integration on high-resistivity silicon. To prove this, extensive investigations have been made concerning the behavior of high-resistivity silicon using these techniques. Also, extremely pure silicon was investigated after high-temperature processing steps (thermal oxidation at 1100°C) to verify the results of [2] and after various processing steps (wafer preparation, pyrolytic oxidation, wet chemical etching, plasma etching, deposition, and patterning of metal films) to show process compatibility.

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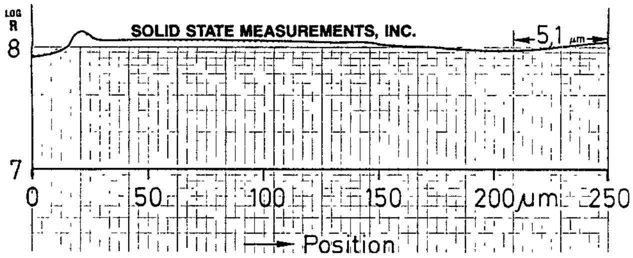

Fig. 2. Spreading resistance of a cleaned wafer versus the position of the probe tips on a 6.8° beveled sample.

II. Behavior of High-Resistivity Silicon

The change in electrical characteristics was investigated with the spreading resistance method and Hall measurements. Spreading resistance (SR) is a known method for dopant profiling [6]. Because the SR probe senses the resistivity in a microscopic sampling volume immediately under the probe tip, one can angle lap a silicon structure and then probe down the beveled surface, obtaining a resistivity versus depth profile.

Investigations were made on 2-in silicon wafers purchased from Wacker Chemitronic with a specific resistance greater than 10 000 Ω·cm. The following results have been obtained: the wafers may show surface state charges, but by proper wafer preparation these can be avoided. Fig. 2 shows the spreading resistance of a polished and cleaned wafer. The wafer was beveled by an angle of 6.84° and the spreading resistance was measured along the beveled surface for a distance of over 250 μm. This corresponds to a depth of more than 30 μm. The spreading resistance remains constant over the whole distance, with a value of about 10^8 Ω. Hall measurements gave a specific resistance of greater than 10 000 Ω·cm, a residual hole concentration of 1.6×10^{12} cm^{-3}, and a Hall mobility of about 380 cm^2/V-s at 300 K.

The epitaxial growth of active layers with the MBE method [4] at temperatures between 550°C and 750°C for about 120 min preceded by thermal cleaning process at 900°C for 5 min produced no change in the electrical characteristics of the high-resistivity silicon bulk material. To show the capability of MBE, a Ga dopant profile on a high-resistivity wafer is shown in Fig. 3. The Ga dopant layer was grown at 550°C. A constant doping level of 1×10^{18} cm^{-3} is found in the MBE layer, and an abrupt junction to the high-resistivity silicon substrate is observed. The substrate doping is not influenced by the MBE process.

Performing a standard BN-diffusion process at 950°C, 20 min yielded the expected diffusion depth profile with preservation of the high quality of the inner bulk material.

The high-temperature thermal oxidation processes at 1100°C of Battershall and Emmons [2], in which resistivity changes from 1400-Ω·cm p-type to 1–10-Ω·cm n-type were observed, were repeated. SR showed that even after 6 h of thermal oxidation at 1100°C, the high resistivity of the bulk material is preserved. However, a lowering of the spreading resistance near the SiO_2/Si interface is observed (Fig. 4). This lowering may be caused by charges in the SiO_2/Si interface which induce a carrier accumulation under the SiO_2/Si interface.

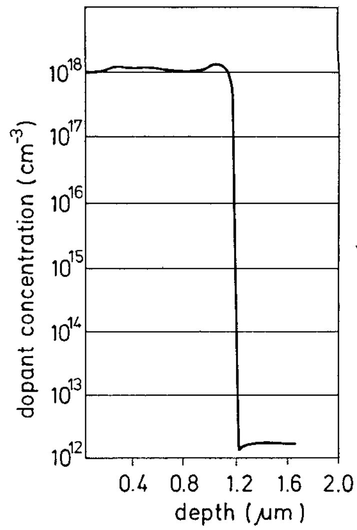

Fig. 3. Ga dopant profile on a high-resistivity silicon wafer grown by MBE at 550°C.

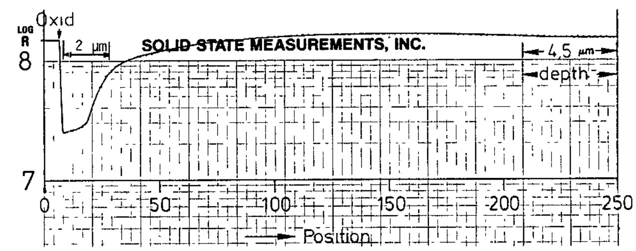

Fig. 4. Spreading resistance as a function of the position of the probe tips on a 6° beveled high-resistivity silicon sample after thermal oxidation at 1100°C for 6 h.

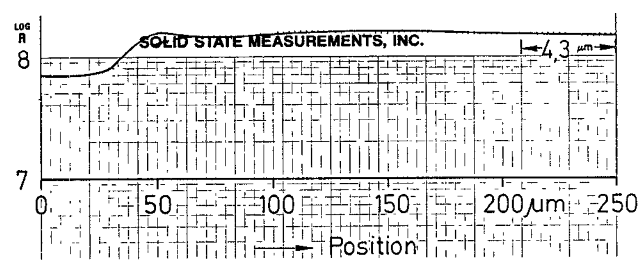

Fig. 5. Spreading resistance as a function of the position of the probe tips on a 5.8° beveled high-resistivity silicon sample after the fabrication process of microstrip ring resonators.

Deposition of metal films, photolithographic patterning, plasma etching, and wet chemical etching show no effects on the high-resistivity silicon. This is shown in Fig. 5, where the spreading resistance measurement is given for a sample on which microstrip resonators were fabricated. During this fabrication process, cleaning procedures, evaporation of metal films, exposure with X-rays, Au-electroplating, and O_2-plasma etching were performed. No difference is found to the spreading resistance curve of the cleaned wafer shown in Fig. 2.

X-ray lithography is a promising technique for the fabrication of future submicron devices [5]. To use this method for the production of millimeter-wave devices, one has to check whether the X-ray exposure influences the conduc-

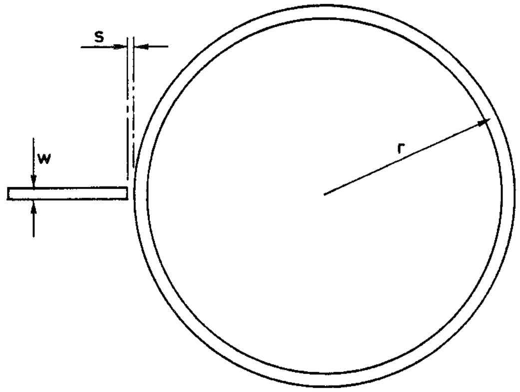

Fig. 6. Ring resonator structure.

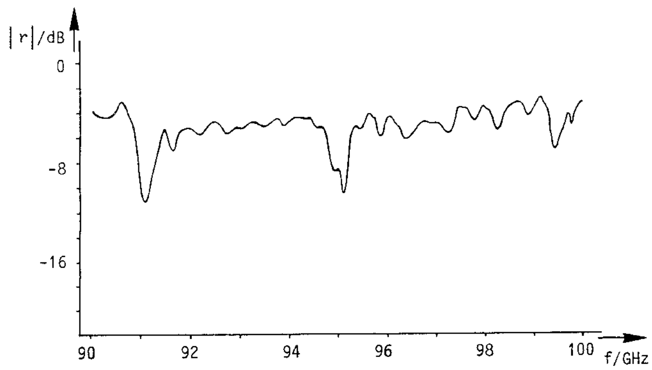

Fig. 7. Reflection coefficient frequency dependence of the ring resonator.

tivity of the exposed material. It could be shown that, even for an exposure of 100 J/cm^2, which is 100 times the exposure with an insensitive resist (PMMA), no degradation of resistivity takes place. Hall measurements confirm these results.

III. Fabrication of Ring Resonators and Linear Microstrip Resonators

Ring resonators and linear microstrip resonators were fabricated using the above-mentioned processes and measured in the frequency range between 90 and 100 GHz. Fig. 6 shows the investigated ring resonator structure. The line width w is 250 μm, the gap width s is 10 μm, and the mean radius r is 3.81 mm. The measured reflection coefficient frequency dependence is depicted in Fig. 7. From these results, we have calculated an $\epsilon_{reff} = 9.2$. This value coincides well with theoretical calculations based on Jansen's formulas [7]. For the attenuation measurements, linear stripline resonators of different lengths were used. Table I gives the data of the measured resonator samples. Fig. 8 shows the measured reflection coefficient frequency dependence of a 40-mm line with a 10 000-$\Omega\cdot$cm silicon substrate. From these results, we have calculated a line attenuation of 0.6 dB/cm, independent of whether X-ray or photolithography was used. On the other hand, microstrip lines on 650-$\Omega\cdot$cm p-silicon substrate showed an attenuation of about 1.4 dB/cm, and lines with a 100–200-$\Omega\cdot$cm substrate showed an attenuation of more than 2 dB/cm.

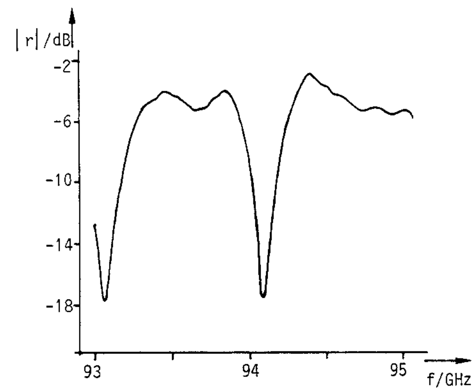

Fig. 8. Reflection coefficient frequency dependence of the linear resonator.

TABLE I
Data of the Linear Resonators

Substrate	silicon
Substrate resistivity	10 000 $\Omega\cdot$cm
Substrate thickness	195 μm
Conductor	gold
Conductor width	190 μm
Conductor thickness	1.5 μm

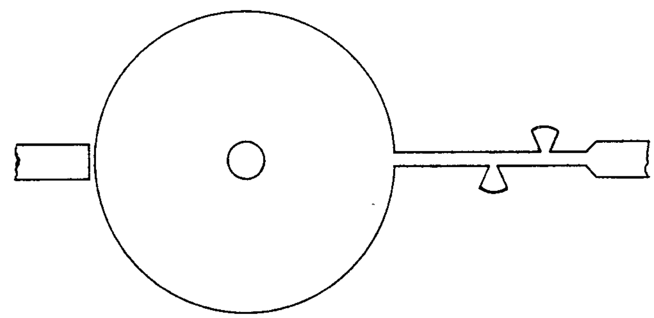

Fig. 9. Layout of the oscillator.

Also, various 10 000-$\Omega\cdot$cm silicon samples were investigated in a reduced height waveguide using a resonator method in the frequency range 75 to 110 GHz. The relative permittivity was found to be 11.68 ($\pm$0.7 percent); the loss tangent was 1.3×10^{-3} ($\pm$30 percent) for unprocessed samples and 1.8×10^{-3} for a sample with an MBE layer of 0.1-μm thickness and a doping concentration of 2×10^{16} Sb/cm^2.

IV. The Integrated IMPATT Oscillator

As the active elements for millimeter-wave generation, IMPATT diodes may be used [3], [8], [9]. For detection and mixing, Schottky diodes will be suitable. We have made preliminary experimental investigations on simple planar structures.

A 95-GHz oscillator has been integrated on a highly insulating silicon substrate. This millimeter-wave microstrip oscillator consists of a planar structure on a 195-μm-thick, 10 000-$\Omega\cdot$cm silicon substrate and a discrete single-drift IMPATT diode as the active element. Fig. 9 shows the layout of the oscillator. The planar millimeter-wave circuit consists of a disk resonator, a transmission line

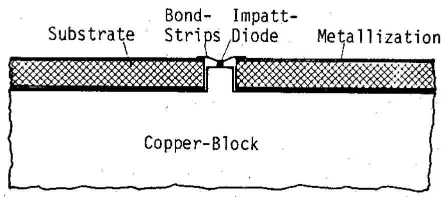

Fig. 10. Cross section through the disk resonator.

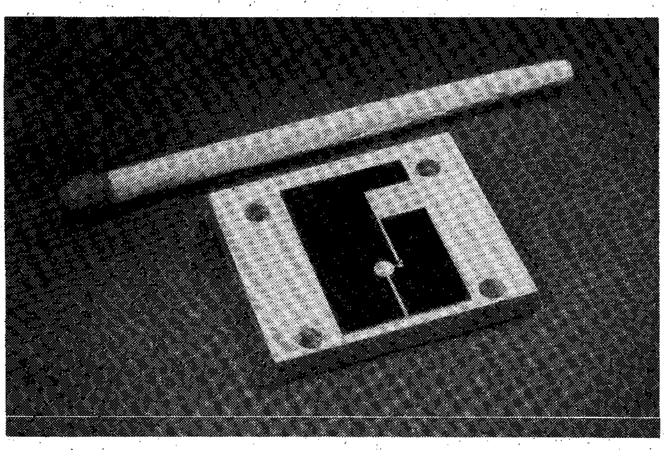

Fig. 11. Photography of the integrated oscillator.

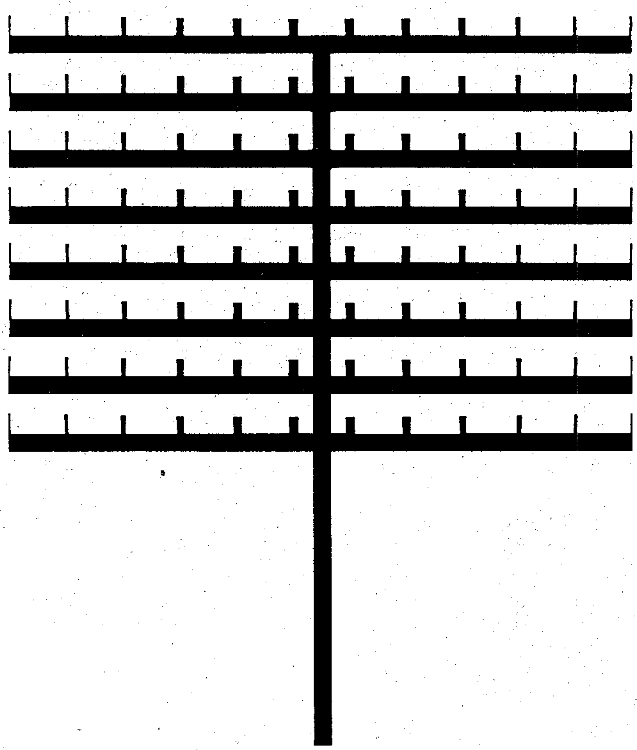

Fig. 12. Layout of the array antenna.

coupled via a gap to the disk resonator, and the dc bias network. The IMPATT diode is mounted in the center hole of the disk resonator and bonded to the resonator via four stripes. Fig. 10 shows the cross section through the disk resonator. The heat sink is a copper block with a mesa reaching into the hole of the planar circuit. Fig. 11 shows a photo of the integrated oscillator.

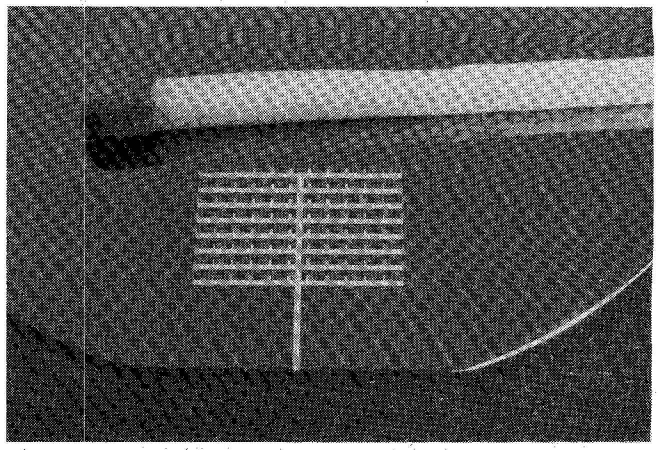

Fig. 13. Photography of the array antenna.

The oscillator needs no tuning elements. Preliminary experimental results are 8 mW of output power with 0.2 percent efficiency at 95-GHz oscillating frequency.

V. Monolithic Planar Stripline Array Antenna

In the millimeter-wave region with small antenna dimensions, a considerable antenna gain may be achieved. At 95-GHz, for example, with 1-cm^2 antenna area, an antenna gain of up to 20 dB may be achieved. This makes the integration of planar stripline antenna structures interesting. Fig. 12 shows the layout and Fig. 13 the photography of a 96-element, two-dimensional microstrip array antenna. We have fabricated the array antenna on a 10 000-$\Omega \cdot$cm silicon substrate with a thickness of 260 μm. The antenna consists of eight lines with twelve $\lambda/2$-antenna elements in each line. In the horizontal direction, a Dolph–Chebyshev design has been used in order to obtain low sidelobes [10]. The antenna dimensions are 8 mm$\times$12 mm. Fig. 14 shows the measured *E*-plane pattern of the antenna at a frequency of 95.7 GHz.

The methods of modern silicon technology will open the way for the monolithic integration of the entire circuit, including the IMPATT diode. Fig. 15 shows the possible configuration of a monolithic integrated transmitter consisting of an oscillator and a stripline antenna on a 1$\times$1-in silicon chip.

VI. Conclusions

High-resistivity silicon can be processed using molecular beam epitaxy (MBE) and X-ray lithography without degradation of the high-resistivity characteristics. Even after high-temperature processing steps of long duration, the bulk material remains highly resistive. For microstrip lines, the attenuation was found to be less than 0.6 dB/cm at 90 GHz. The feasibility of this silicon planar technology for millimeter-wave circuits has been demonstrated by the fabrication of a hybrid–monolithic integrated 95-GHz oscillator and a planar microstrip antenna.

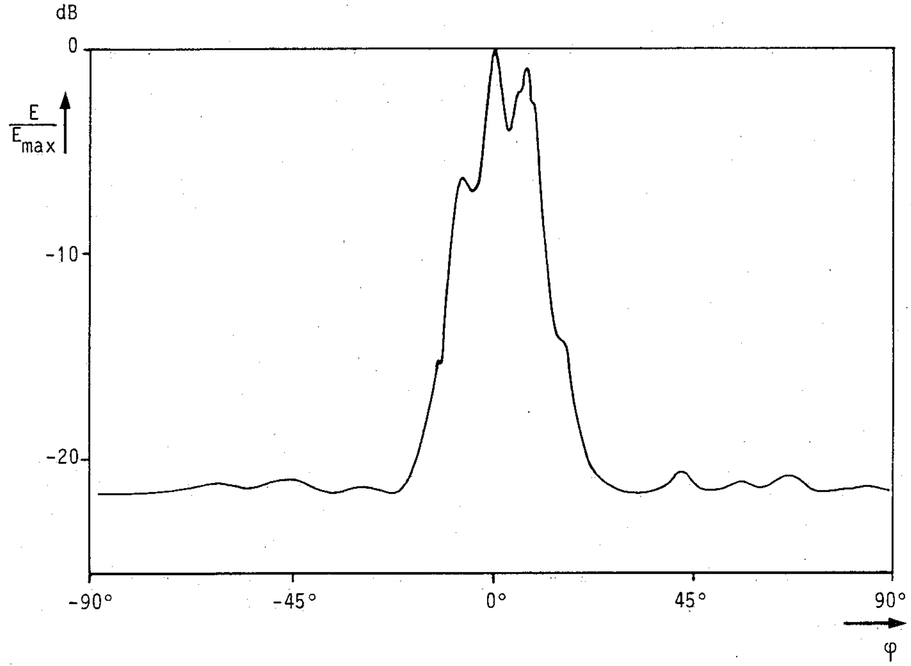

Fig. 14. *E*-plane radiation pattern of the array antenna.

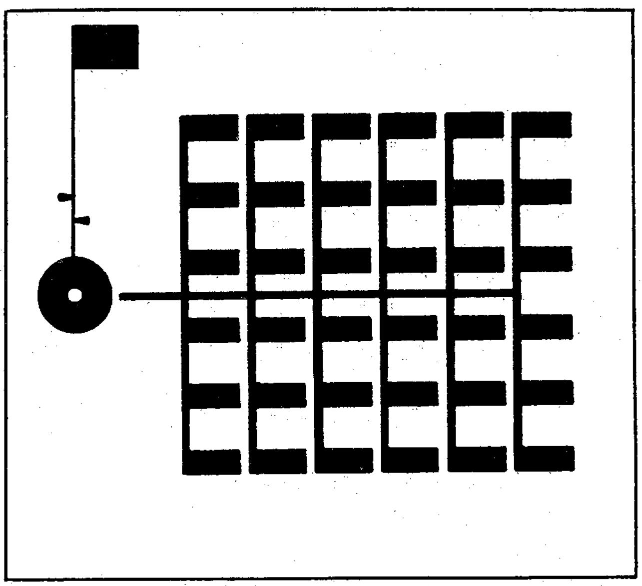

Fig. 15. Monolithic integrated millimeter-wave transmitter.

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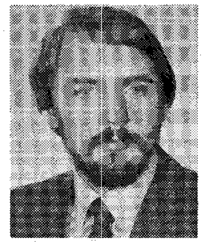

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