SILICON HIGH RESISTIVITY SUBSTRATE MILLIMETER-WAVE TECHNOLOGY

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Abstract

The application of the VLSI-techniques 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. Ring- and linear microstrip resonators were fabricated on 10 000 Ohm cm silicon. For linear microstrip resonators, the attenuation was found to be less than 0.6 dB/cm at 90 GHz. A 95 GHz impatt oscillator has been integrated on a highly insolating silicon substrate in a combined monolithic-hybrid technique. The oscillator needs no tuning elements. From preliminary experimental results 8 mW output power with 0.2 % efficiency at 95 GHz oscillating frequency has been obtained.

1. Introduction

Highly insulating silicon is very promising as the base material for future applications in planar millimeter-wave circuits /1/. These circuits may be monolithic integrated as well as hybrid-monolithic integrated. For frequencies above 40 GHz and a resistivity of the substrate material greater than 2000 Ohm cm, the dominant loss mechanism is the skin effect in the conductors (Fig. 1). 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 integration it was found that silicon undergoes resistivity changes during high temperature processing steps and the attenuation for microstrip lines increased to untolerable 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/.

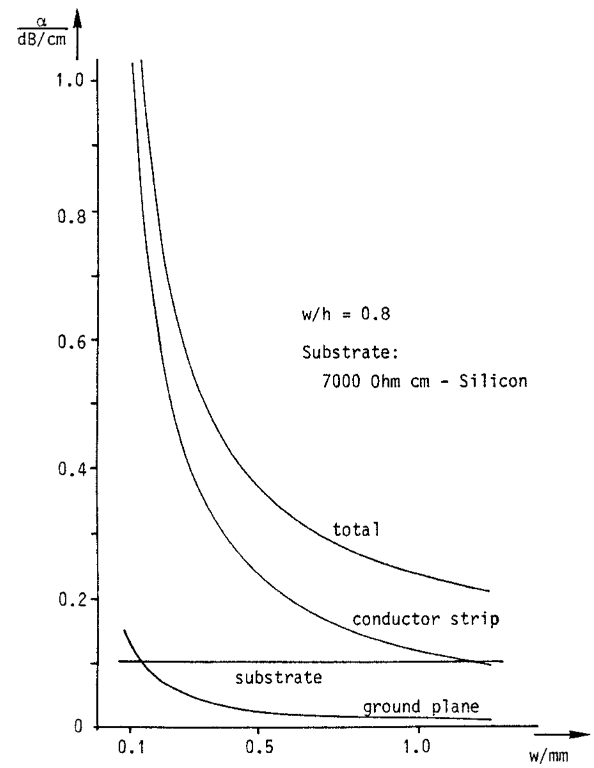

Fig. 1: Calculated attenuation coefficient of microstrip lines on silicon substrate

With the VLSI technique of molecular beam epitaxy (MBE) for the growth of active, monocrystalline films at moderate temperatures /4/ (550-750°C) and with X-ray lithography for lateral patterning of submicron lines /5/, modern techniques are available to us for a promising monolithic

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integration on high resistivity silicon. To prove this, extensive investigations have been made concerning the behaviour 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 state of the art processing steps (wafer preparation, pyrolitic oxidation, wet chemical etching, plasma etching, deposition and patterning of metal films) to show process compatibility.

2. Behaviour 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. 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 bevelled surface obtaining a resistivity vs depth profile.
Investigations were made on commercially available 2"-silicon wafers with a specific resistance greater than 10 000 Ohm cm. The following results have been obtained: The starting wafers may show surface state charges but by proper wafer preparation these can be avoided. Hall measurements gave a specific resistance of greater than 10 000 Ohm cm, a residual hole concentration of 1.6 x 10^{12} cm^{-3} and a hole mobility of about 380 cm^2/Vs at 300 K. Pyrolitic oxidation performed at 420°C (14 min) can reduce the surface state charges so that the high resistance of the bulk material is preserved.
The epitaxial growth of active layers with the MBE method at temperatures between 550°C and 750°C and a foregoing thermal cleaning process at 900°C produced no change in the electrical characteristics of the high resistivity silicon bulk material.
Performing a standard BN-diffusion process at 950°C, 20 sec 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 Ohm cm p-type to 1-10 Ohm cm n-type were observed, were repeated. SR showed that even after 6 hours of thermal oxidation at 1100°C, the high resistivity of the bulk material is preserved. However, depending on the cleanliness of the oxidation process a more or less deep doped layer near the surface is observed (Fig.2). Hall measurements in some cases showed n-conductance with a resistivity of 100 Ohm cm. According to the SR measurements this is due to a contamination layer at the surface, the high resistivity of the bulk material is preserved. The conducting contamination layer, however, may increase the attenuation to intolerable values.
Deposition of metal films, photolithographic patterning, plasma etching and wet chemical etching show no effects on the high resistivity silicon.

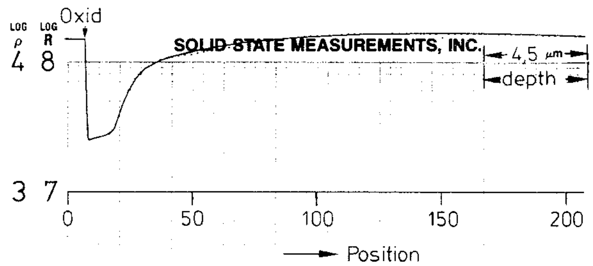

Fig. 2: Spreading resistance as a function of the probe tips on a 6° bevelled silicon sample after a thermal oxidation at 1100°C for 6 h

X-ray lithography is a promising technique for fabrication of future submicron devices. To use this method for the production of millimeter-wave devices, one has to check whether the X-ray exposure influences the conductivity of the exposed material. It could be shown that, even for an exposure of 100 times the dose of a normal exposure with an insensitive resist, no degradation of resistivity takes place. From Hall measurements, one can conclude that the resistivity is increased in some cases.

3. 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. 3 shows the investigated ring resonator structure. The line width, w, is 250 μm, the gapwidth, s, is 10 μm and the mean radius, r, is 3.81 mm. The measured reflection coefficient frequency dependence is depicted in Fig. 4. From these results, we have calculated an ε_{reff} = 9.2. This value coincides well with theoretical calculations based on Jansens formulae /6/. For the attenuation measurements, linear strip line resonators of different lengths were used. Table 1 gives the data of the measured resonator samples. Fig. 5 shows the measured reflection coefficient frequency dependance of a 40 mm line with a 10 000 Ohm cm silicon substrate. From these results we have calculated a line attenuation of 0.6 dB/cm independent of whether X-ray or photo-lithography was used. On the other hand, microstrip lines on 650 Ohm cm p-silicon substrate showed an attenuation of about 1.4 dB/cm and lines with a 100 - 200 Ohm cm substrate, an attenuation of greater than 2 dB/cm.

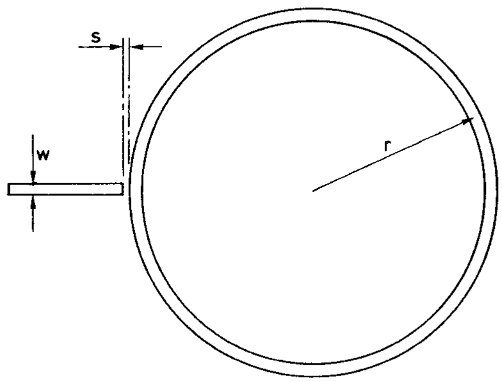

Fig. 3: Ring resonator structure

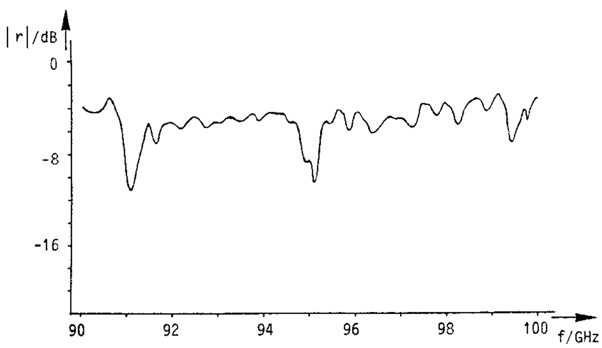

Fig. 4: Reflection coefficient frequency dependence of the ring resonator

Also various 10 000 Ohm cm silicon samples were investigated in a height reduced waveguide using a resonator method in the frequency range 75 to 110 GHz. The relative permittivity was found to be 11,68 (±0.7%), the loss tangent 1.3×10^{-3} (±30%) for unprocessed samples and 1.8×10^{-3} for a sample with an MBE layer of 0.1 um thickness and a doping concentration of 2×10^{16} Sb/cm^2.

Substrate	Silicon
Substrate resistivity	10 000 Ohm cm
Substrate thickness	195 µm
Conductor	Gold
Conductor width	190 µm
Conductor thickness	1.5 µm

Table 1: Data of the linear resonators

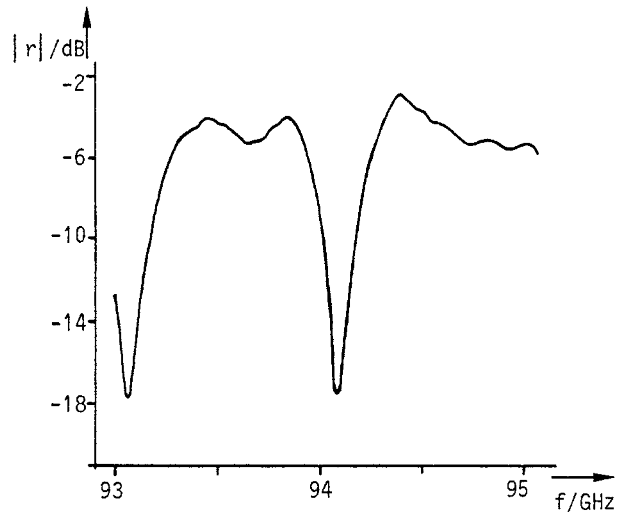

Fig. 5: Reflection coefficient frequency dependence of the linear resonator

4. Monolithic-hybrid integrated impatt oscillator

As the active elements for millimeter wave generation impatt diodes may be used /3,7,8/. 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 isolating silicon substrate in a combined monolithic-hybrid technique. This millimeter-wave microstrip oscillator consists of a planar structure on a 195 µm thick 10 000 Ohm cm silicon substrate and a discrete single-drift impatt diode as the active element. Fig. 6 shows the layout of the oscillator. The planar millimeter-wave circuit consists of a disk resonator, a transmission line 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. 7 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 8 shows the photo of the hybrid-monolithic integrated oscillator.

The oscillator needs no tuning elements. From preliminary experimental results 8 mW output power with 0.2 % efficiency at 95 GHz oscillating frequency has been obtained.

1" x 1" silicon chip. An antenna structure with an area of 15 x 15 mm^2 will provide more than 20 dB gain.

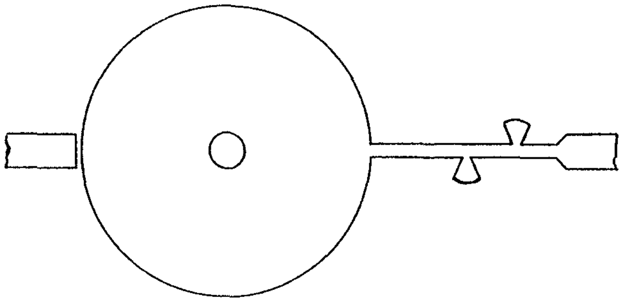

Fig. 6: Layout of the oscillator

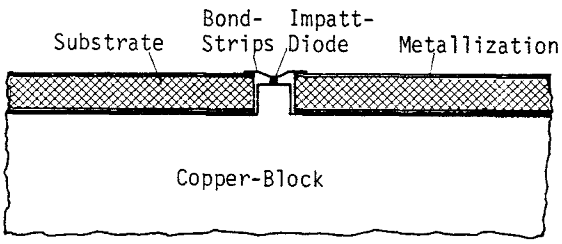

Fig. 7: Cross section through the disk resonator

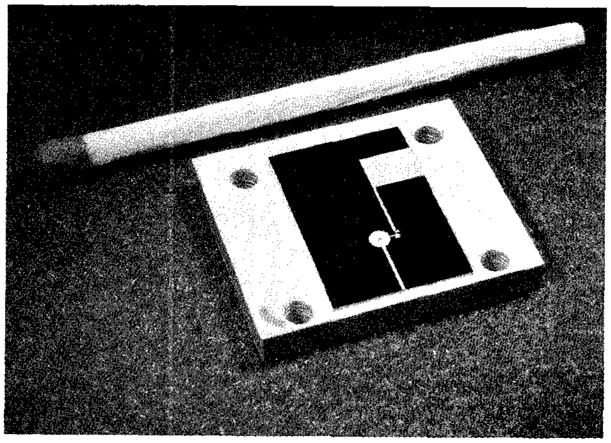

Fig. 8: Photo of the hybrid-monolithic integrated oscillator

The methods of modern VLSI silicon technology will open the way for a monolithic integration of the whole circuit, including the impatt diode. Fig. 9 shows the possible configuration of a monolithic integrated transmitter consisting of an oscillator and a strip line antenna on a 1" x 1" silicon chip. An antenna structure with an area of 15 x 15 mm^2 will provide more than 20 dB gain.

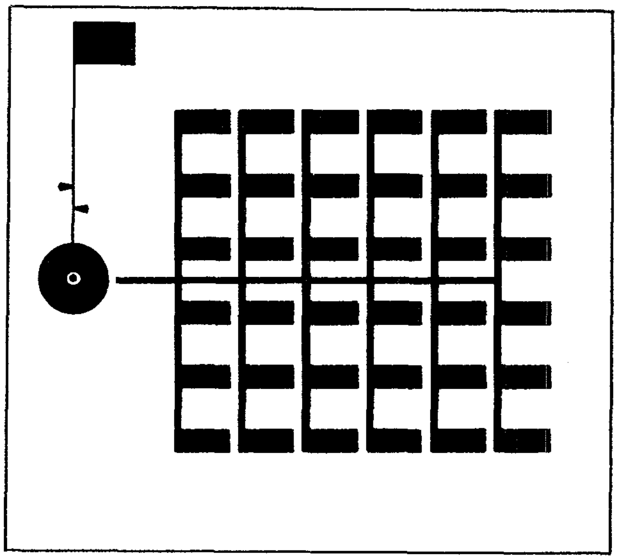

Fig. 9: Monolithic integrated millimeter-wave transmitter

Conclusion

High resistivity silicon can be processed with the VLSI-techniques molecular beam epitaxy (MBE) and X-ray lithography without deterioration of the high resistivity characteristics. Even after high temperature processing steps of long duration, the inner of 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 feasability of this silicon planar technology for millimeter-wave circuits has been demonstrated by the fabrication of a hybrid-monolithic integrated 95 GHz oscillator.

References

/1/ Rosen A. et al.; "Silicon as a Millimeter-Wave Monolithically Integrated Substrate - A New Look"; RCA Review, Vol. 42, Dec. 1981, pp. 633 - 660

/2/ Battershall B.W., Emmons S.D.; "Optimization of Diode Structures for Monolithic Integrated Microwave Circuits"; IEEE, Vol. SC-3, June 1968, pp. 107 - 112

/3/ Stabile P.J.; Rosen A,; "A Silicon Technology for Millimeter-Wave Monolithic Circuits"; RCA Review, Vol. 45, Dec. 1984, pp. 587 - 605

/4/ Kasper E.; Wörner K.; "High Speed Integrated Circuit Using Silicon Molecular Beam Epitaxy (SI-MBE)"; J. Electrochem. Soc. : Solid-State Science and Technology, Vol. 132, No. 10, Oct. 1985, pp. 2481 - 2486

/5/ Strohm K.M.; Hersener J.; Herzog H.J.; "Stress compensated Si-membrane masks for X-ray lithography with synchrotron radiation"; Eurocon' 86 Proceedings 21. - 23. Apr. 1986, Paris, AI.4

/6/ Jansen R. H.; Kirschning M.; "Arguments and an Acurate Model for the Power-Current Formulation of Microstrip Characteristic Impedance"; AEÜ, Vol. 37, March 1983, pp. 108 - 112

/7/ Glance B.S.; Schneider M.V.; "Millimeter-Wave Microstrip Oscillators"; MTT, Dec. 1974, pp. 1281 - 1283

/8/ Morgan G.B.; "Microstrip Impatt-Diode Oscillator for 100 GHz"; Electron. Lett., Vol. 17; No. 16; Aug. 1981; pp. 570 - 571

Acknowledgement

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