indicate that the R_s ratios increase with increasing frequency. The continuing investigation is expected to yield additional useful information.

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References

[1] T. S. Thorp, "R.F. conductivity in copper at 8 mm wavelength," *Proc. Inst. Elec. Eng.*, vol. 101, pt. III, pp. 357–359, 1954.
[2] F. A. Benson and D. H. Stevens, "Rectangular waveguide attenuation at millimeter wavelength," *Proc. Inst. Elec. Eng.*, vol. 110, pp. 1008–1014, 1967.
[3] ——, "Surface properties of waveguides," presented at the 17th Int. Scientific Radio Union General Assembly, Warsaw, Poland, August 1972.
[4] F. J. Tischer, "Anomalous skin effect of single-crystal copper in the millimeter-wave region at room temperature," *Physics Lett.*, vol. 47A, pp. 231, 233, 1974.
[5] F. J. Tischer and F. Jalali, "Resonant cavities for the measurement of the surface resistance of conductors at millimeter wavelength," *Rev. Sci. Instrum.*, vol. 46, pp. 11–14, 1974.
[6] F. W. Young and T. R. Wilson, "Acid cutting and acid polishing of copper crystals," *Rev. Sci. Instrum.*, vol. 32, pp. 559–562, 1961.
[7] A. B. Pippard, *The Dynamics of Conduction Electrons.* London, England: Gordon and Breach, 1965.
[8] F. J. Tischer, "Excess surface resistance due to surface roughness at 35 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 566–569, 1974.
[9] M. A. Heald and C. B. Wharton, *Plasma Diagnostics with Microwaves.* New York: Wiley, 1965.
[10] *MM-Wave Test Equipment*, Hitachi Electronics, Ltd., Catalog DW-E002, p. 65.
[11] *Millimeter-Wave Components*, Baytron Comp., Medford, MA, p. 29.
[12] S. Ishii and K. Ohi, "Advanced loss reduction techniques in millimeter waveguide instruments," presented at the 1975 IEEE/S-MTT Int. Microwave Symp.
[13] S. Ramo *et al.*, *Fields and Waves in Communication Electronics.* New York: Wiley, p. 423, 1965.

Short Papers

200-GHz 50-mW CW Oscillation with Silicon SDR IMPATT Diodes

T. ISHIBASHI AND M. OHMORI

Abstract—**Silicon SDR IMPATT diodes have been operated continuously in 200- and 300-GHz bands. A p^+-n junction structure was formed by thermal diffusion of boron and ion implantation of phosphorus ions. CW output power of 50 mW was obtained at 202 GHz with 1.3-percent conversion efficiency. At 301-GHz CW output power of 1.2 mW was observed.**

Introduction

Silicon IMPATT diodes over the 100-GHz range have been reported by several authors with SDR [1], [2] and DDR [3] structures. This short paper describes the performance of Si IMPATT diodes designed for 200-GHz-band operation. Efficiency of IMPATT diodes near the submillimeter-wave region is decreased by several effects. Among them, saturation of the ionization rate in the high electric field and degradation of transfer efficiency cause serious effect. According to the ionization rate of Si presented by Grant [4], $d\alpha/dE$ (where α is the ionization rate and E is the electric field) has a peak value of about $E = 5 \times 10^5$ V/cm and decreases at higher fields. For 200-GHz-band operation, SDR diodes require a depletion layer width of about 0.15 μm, based on the optimum transit angle 0.6π.

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In this case, the maximum electric field in an active region becomes higher than 1×10^6 V/cm for an abrupt junction, and the extrapolated value of $d\alpha/dE$ is reduced to half of its peak value. Therefore, the negative conductance will be reduced considerably in the 200-GHz band. Diode transfer efficiency is given as follows [5]:

$$(1 - R_s \cdot B_d^2/G_m)^3, \qquad \text{for } B_d \gg G_m$$

where R_s is the diode series resistance, B_d is the susceptance, and G_m is the small-signal negative conductance. Provided that B_d is proportional to diode capacitance and depletion layer width according to $(\text{frequency})^{-1}$, it results that $B_d \propto (\text{frequency})^2$ for a constant diode area. In order to maintain the high value of transfer efficiency, it is important to reduce the diode series resistance R_s.

Device Fabrication

A p^+-n-n^+ structure was fabricated with a Si epitaxial wafer by the BN diffusion process of boron and ion implantation of phosphorus ions. An original wafer has an n^- epitaxial layer of 0.4-μm thickness on a heavily doped n^+ substrate. After diffusion of boron for 4 min at 900°C, an n-type drift region was formed by double energy implantation into an n^- layer by (111) off-channel direction. Two steps of dose were $4.4 \times 10^{12}/\text{cm}^2$ with acceleration energy 60 keV and 1.0×10^{13} cm^2 with 160 keV. An 850°C 10-min heat treatment produced nearly 100 percent activated phosphorus ions. Carrier density measured by the capacitance–voltage method is given in Fig. 1, which shows a uniform n-type region of carrier density 5×10^{17} cm^3. The

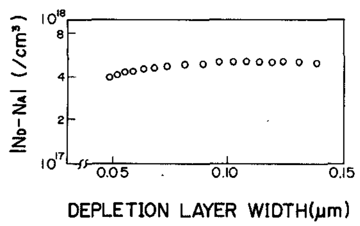

Fig. 1. Carrier density profile of the wafer.

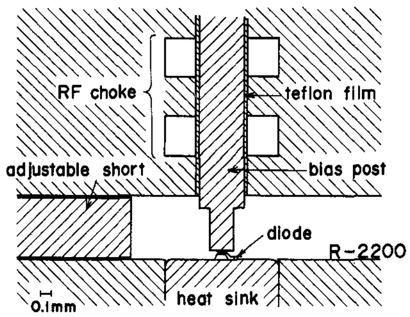

Fig. 2. Waveguide circuit with a tuning cap structure for 200-GHz-band operation.

breakdown voltage and depletion layer width at breakdown are 7.4 V and 0.14 μm, respectively. After annealing, the wafer was thinned to several microns, metallized by evaporating Ti–Au, separated into individual pellets by an air-brasive method, and bonded on a heat sink with a quartz stud. DC series resistance was 0.27 Ω for a diode of 23-μm diameter.

Oscillation Characteristics

Microwave measurements were made in the full-height waveguide (R-2200; 1.092 × 0.546 mm^2) with a tuning cap cavity shown in Fig. 2. Diode tuning was done by selecting the proper bias post and sliding the adjustable short. Sensibility of the power meter has been calibrated against a dry calorimeter. The oscillation frequency was measured by a two-dip-type frequency meter and by detecting a standing wave using a point contact diode mount with a movable short. High-pass filters were used to check the frequency measurements. Input–output characteristics for best performance are given in Fig. 3. CW output power of 50-mW at 202 GHz and 44 mW at 214 GHz were obtained, with conversion efficiencies of 1.3 and 1.2 percent, respectively. At 50-mW output power, the dc bias voltage and current were 9.2 V and 410 mA, respectively. When a high-pass filter with 230-GHz cutoff was inserted at the output port of the IMPATT diode mount, an oscillation in the 300-GHz band was observed. CW output power of 1.2 mW at 301 GHz was obtained for a diode with a diameter of 18 μm. When the high-pass filter was removed leaving the same tuning condition, a $\frac{2}{3}$ frequency of the 300-GHz band was observed. These facts imply that an oscillation of the fundamental frequency in the 100-GHz band would be excited. But the frequency is below the cutoff frequency of R-2200 waveguide used here.

In summary, Si IMPATT diodes have operated in the 200-GHz band with CW output powers as high as 50 mW. CW operation with practical power can be expected over a 300-GHz band.

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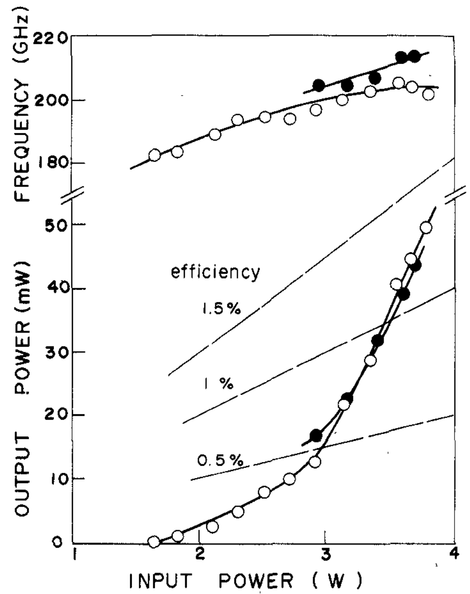

Fig. 3. 200-GHz-band output power and frequency versus input power for diode with a diameter of 23 μm and series resistance of 0.27 Ω. Open circles and solid circles represent the characteristics with two different caps.

References

[1] T. Ishibashi, T. Makimura, and K. Suzuki, "Si SDR IMPATT diodes for 150 GHz operation," Paper Tech. Group on Elec. Device, IECE, Jap., ED74-33, August 1974.
[2] D. H. Lee and R. S. Ying, "Ion-implanted complementary IMPATT diodes for *D*-band," *Proc. IEEE*, vol. 62, no. 9, pp. 1295–1296, Sept. 1974.
[3] M. Ino, T. Makimura, and H. Yamazaki, "High efficiency 80 GHz and 150 GHz band Si DDR IMPATT diodes," *Trans. IECE Japan*, vol. 58-C, no. 11, pp. 689–690, Nov. 1975.
[4] W. N. Grant, "Electron and hole ionization rates in epitaxial silicon at high electric field," *Solid State Elec.*, vol. 16, pp. 1189–1203, 1973.
[5] J. W. Gewartowski, "The effect of series resistance on avalanche diode (IMPATT) oscillator efficiency," *Proc. IEEE*, vol. 56, no. 6, pp. 1139–1140, June 1968.

A 230-GHz Radiometer System Employing a Second-Harmonic Mixer

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***Abstract*—A radiometer system for use in the $\lambda \sim 1.3$ mm ($\nu \sim 230$ GHz) region has been constructed and used for radio astronomical observations. A second-harmonic mixer employing a single Schottky diode downconverts the incident power to an IF frequency of ~1400 MHz. The measured double-sideband system noise temperature is 6000 K (noise figure = 13 dB) and the double-sideband mixer conversion loss is calculated to be 10 dB. The mixer is tunable over a range of at least 15 GHz.**

Introduction

The development of microwave receivers for wavelengths shorter than 2 mm has been hampered by the lack of local oscillators to pump frequency downconverters. One approach to this problem has been to produce a local oscillator (LO) signal by multiplication of existing lower frequency sources. It has been

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