Excess Conduction Losses at Millimeter Wavelengths

FREDERICK J. TISCHER, FELLOW, IEEE

Abstract—**Excess conduction losses and discrepancies between theoretical and measured values of waveguide attenuation and surface resistance are investigated. The results of comprehensive experiments to isolate the effects contributing to the discrepancies and excess losses are presented.**

Introduction

ACCURATE VALUES of the surface resistance of conductors are very important to the efficient utilization of the millimeter-wave region which is under development for applications in communications, radar, and radio astronomy at present. The attenuation of waveguides, the Q factors of resonators, and the loss characteristics of networks depend on these data. Reliable data, however, are not available in this frequency range since discrepancies exist between measured and theoretical values obtained by customary skin-effect and scattering theory. In addition, the explanations for these discrepancies and experimental results published by different investigators do not agree.

The discrepancies were originally observed in microwave engineering (1–20 GHz) and later at millimeter wavelengths (20–300 GHz). They are relatively low at 10 GHz (2–5 percent) but become appreciable in the millimeter-wave region above 30 GHz. Increases of the surface resistance of 50 to 100 percent have been observed at 35 and 70 GHz. The discrepancies have been investigated frequently in device-oriented studies at frequencies below 12 GHz and in a few cases at millimeter wavelengths [1]–[3]. Macroscopic surface roughness, work hardening due to machining, oxidation, and cavity-type surface irregularities [3] were indicated as causes of the discrepancies. Special processing methods, such as electropolishing, etching, and annealing, applied to waveguides and resonators, have resulted in improvements, particularly in the case of originally lossy surfaces. In general, however, the reported results have been inconclusive and often contradictory.

This paper describes primarily experimental efforts 1) to analyze the observed discrepancies and 2) to generate new reliable data applicable to systems and component design.

Basic Approach

In order to obtain conclusive results, emphasis in these efforts has been placed on two requisites: 1) high accuracy of the electrical measurements and 2) satisfactory definition and description of the surfaces under investigation. High accuracy is necessary for separation and determination of the various effects contributing to excess losses and discrepancies. Accurate definition and description of the surface conditions make the results meaningful and practical.

The most appropriate quantity for describing the electrical surface characteristics of conductors at high frequencies is the surface resistance R_s which is the real part of the complex surface impedance. The attenuation of waveguides is directly, and the Q factor of resonators is inversely, proportional to this quantity.

Two methods are commonly used to determine the surface resistance. One is based on measurement of the attenuation of waveguides and the other on evaluation of the measured Q factors of resonators. Both methods were applied in this research. In the greater part of the work, rectangular cavity resonators were used. Their plane walls facilitated fabrication, processing, and measurement of nonelectrical surface characteristics such as roughness. Most of the experiments were carried out on copper surfaces.The attenuation measurements included silver waveguides since most published data are available for this kind of guide.

The investigation had three parts. The first part was a set of experiments designed to separate the causes of the discrepancies and excess losses and to find an intrinsic value of the surface resistance of conductors. The second part consisted of artificially creating surface roughness and then determining its effect on surface resistance. In the third part, highly accurate measurements of the attenuation of commercially available waveguides were made. These measurements were used to assess the validity of the existing published figures, and to establish relationships between the fundamental data of the other phases of the investigation and those encountered in practical engineering.

Anomalous Skin Effect of Single-Crystal Copper

Previous experiments analyzing the effects of surface roughness carried out at 35 GHz indicated the existence of a minimum experimentally obtainable value of surface resistance. The value was considerably higher than the theoretical figure and could not be reduced by improved polishing methods and special surface preparation such as chemical polishing, electropolishing, and annealing. These results led to an attempt to find the intrinsic surface resistance of copper at millimeter wavelengths and room temperature. Since highly accurate equipment and advanced measurement methods were available, it was felt that meaningful results could be obtained [4].

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The author is with the Department of Electrical Engineering, North Carolina State University, Raleigh, NC 27607.

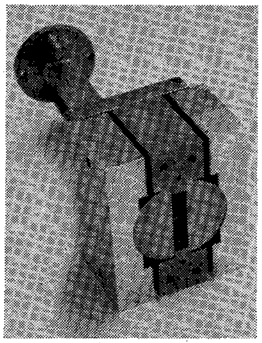


Fig. 1. Cross-sectional structure of cavity resonators.

The basic approach consisted of measuring the Q factor of a rectangular cavity in which the plane surfaces to be investigated formed the side walls. After testing three types of cavities [5], the final experiments were carried out by use of a rectangular cavity with the cross section shown in Fig. 1. In this cavity, the side walls are formed by half-cylinders pressed against spacers attached to the end walls. The top and bottom walls are parts of the spacers. Holes in the end walls couple the cavity to input and output waveguides. By carefully shaping the spacers and by using a torque wrench, satisfactory repeatability of measurements and agreement of results with those of a "standard cavity" [5] were achieved. The dimensions of the cavity were so optimized that the major contribution to the unloaded Q factor of the cavity resulted from the side walls. The following equation shows the relationships. The Q factor of the cavity is given by

$$1/Q_{\text{cavity}} = 1/Q_s + 1/Q_{t,b} + 1/Q_e$$

where Q_s, $Q_{t,b}$, and Q_e are the Q factors associated with the side walls, the top and bottom walls, and the end walls, respectively. The cavity was optimized so the side walls give a maximum contribution to the cavity losses as shown in Fig. 2. For a cavity 4.4 mm wide, the contribution by the side walls is about 90 percent.

In order to find the intrinsic value of the surface resistance, the surfaces to be evaluated were very carefully prepared. They were prepared and handled in ways that eliminated any effects that increase the surface resistance. Also, their nonelectrical characteristics were well known [6]. They were cut from single-crystal rods with a purity of 99.999 percent. The cutting was done with an acid saw and the polishing, with a chemical polishing wheel developed by Oak Ridge National Laboratories. The side wall surfaces were of the (100) type of copper crystal; they were electropolished, washed, dried, and annealed in hydrogen. They were also kept and transported in hydrogen and were mounted in an argon-filled glove box in the cavity. Argon was kept flowing through the cavity during transfer into the millimeter-wave circuitry and during measurements. The measurements gave the following results:

$$Q_{\text{cavity, unloaded}} = 4971 \qquad R_{s\,\text{side walls}} = 0.0554\ \Omega$$
$$Q_{\text{side walls}} = 5579 \qquad R_s'{}_{\text{computed}} = 0.0488\ \Omega.$$

The error of the determination of Q_s, including disassembly and reassembly of the cavity, did not exceed ± 1 percent. The value of R_s' was computed from the handbook value of the conductivity of pure copper at room temperature, $\sigma_0 = 5.80 \times 10^7$ S/m. The results thus indicate that the measured surface resistance of copper exceeds the computed value by a factor $r_x = R_s/R_s' = 1.135 \pm 0.02$. The result implies that under the described conditions of room temperature and 35 GHz the intrinsic surface resistance of single-crystal copper is $R_s = 0.0554\ \Omega$. This basically means that the skin effect is anomalous at millimeter wavelengths at room temperature. It is probably associated with anomalous scattering of the electrons near the copper surface.

The effect, however, is not identical to that observed at low temperature [7] when the skin depth is a fraction of the mean free path. Calculations have shown that this effect could account at room temperature for a deviation of one or two percent of R_s at most.

EFFECTS OF SURFACE ROUGHNESS

This part of the investigation was based on the assumption that roughness is just one of several effects contributing to the excess losses, and that the surface elements of a wavy rough surface and a highly polished surface have practically identical microscopic electrical properties. In accordance with these assumptions, the walls of the cavities used in these experiments were artificially roughened and the Q factors were measured. The results were evaluated for values of surface resistance for various degrees of roughness which, in turn, were normalized with regard to the surface resistance of highly polished walls. The ratios obtained in this way are a measure of the effect of roughness on excess losses. The experiments were repeated several times, resulting in consecutively improved procedures for surface preparation and evaluation and increased accuracy of the electrical measurements.

An H-guide resonator was applied in the first set of experiments [8], but was later replaced by rectangular cavities [4] optimized for the special purpose. Most recently the cavity shown in Fig. 1 was used. One-dimensional roughness was generated by grinding the side walls (flat surfaces of the half-cylinders) on specially designed grinders using carefully selected abrasive papers. One of the grinders was designed so that two strips at the edges of the side walls maintained their original highly polished state in the region where contact was made with the top and bottom spacers. Under experimental conditions the direction of the electrical currents on the side walls was perpendicular to the ridges of the roughness pattern.

The degree of roughness was determined in several ways. A stylus-type profilometer calibrated in rms values was used to find the roughness mechanically. The instrument was recalibrated since it was felt that the manufacturer's calibration may not have been valid for the one-dimensional roughness typical of the present experiments. The calibration was done by photomicrography. Several copper samples were ground with different-grade abrasive papers, cut at locations with uniform roughness, and embedded in Bakelite. After grinding and polishing, the boundary line between the ground copper surface and the Bakelite was photographed under a microscope with monochromatic light. A

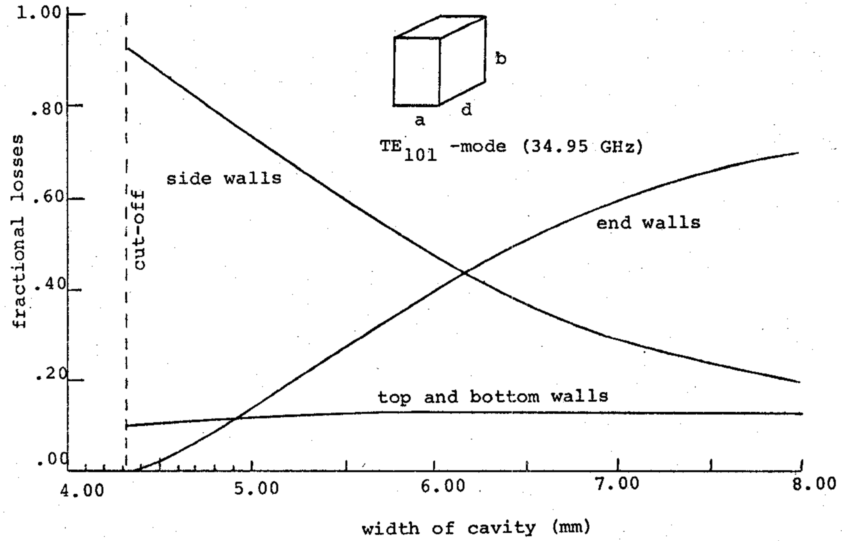
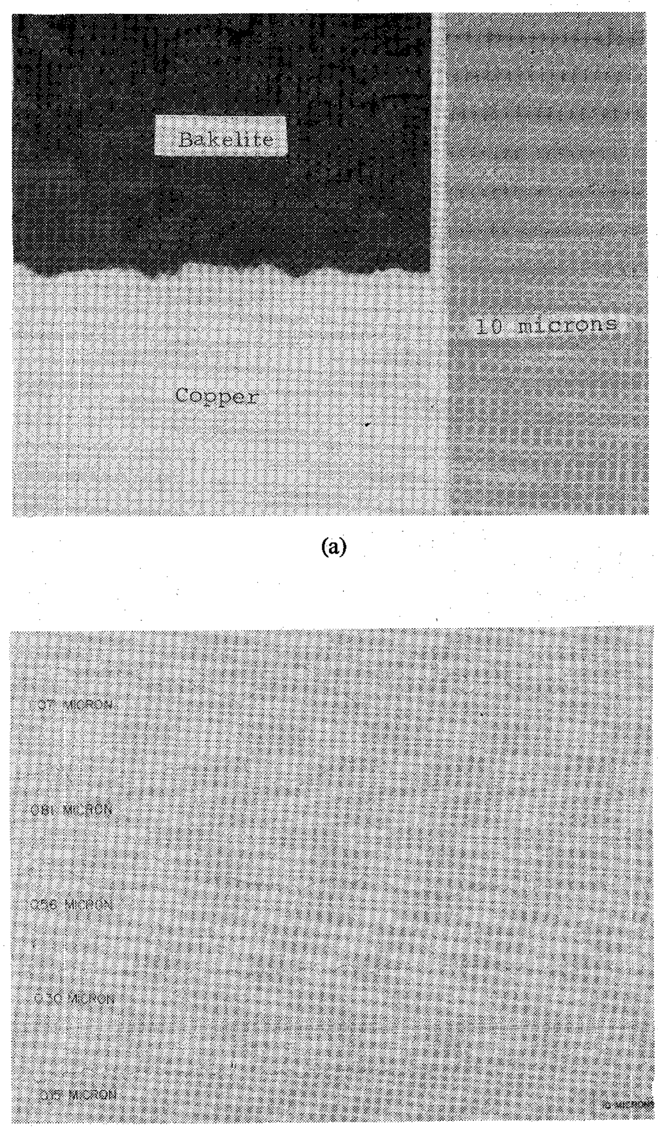


Fig. 2. Fractional loss contributions of cavity walls. Cavity dimensions: a = 4.4 mm, b = 20.8 mm, d = 25.4 mm.

typical example of an enlarged print showing the surface profile can be seen in Fig. 3(a). The profiles were projected onto a screen and traced on large strips of paper. The projection distance was chosen such that the lines of a 10-μm grid were 50 mm apart on the screen, giving an overall magnification of 5000. Fig. 3(b) shows the profile graphs for five samples, each with different degrees of roughness. Evaluation of the graphs gave the rms values, the probability distributions, and the values of line length of the profile graphs. This latter quantity, for one-dimensional roughness, is a measure of the area increase due to roughness.

The rms values found in this way were then used for the calibration of the profilometer. Corresponding photomicrographic values and meter readings are listed in Table I. The table shows that the profilometer readings were too low. This discrepancy may be explained by the large radius (12.5 μm) of the tip of the profilometer stylus which cannot completely follow the surface profile. Additional tests were made by optical methods using reflectance measurements. In these experiments, the angular spread of a laser beam caused by one-dimensional roughness served as a measure of the rms height variation [8].

After preparatory studies of sample surfaces and calibration of the profilometer, several sets of Q-factor measurements were made using the rectangular cavity. The results were then evaluated to give the ratio of the surface resistance R_s' for rough surfaces versus highly polished side walls R_{sp}. A representative example of the results is given in Fig. 4. It shows the resistance ratio for a copper surface versus the rms surface roughness for currents flowing across the grooves associated with the roughness. The diagram indicates that the surface conductance of a rough surface with an rms of about 1 μm increases to about 1.33 of the value of the highly polished surface. It is interesting that this corresponds to the increase in the surface area due to roughness at this particular rms value. No similar agreement was found at small degrees of roughness when



(a)

(b)

Fig. 3. (a) Enlarged prints showing the boundary between a rough copper surface and Bakelite and a 10-μm grid for scaling. (b) Profile graphs of sample surfaces. Profilometer readings at left.

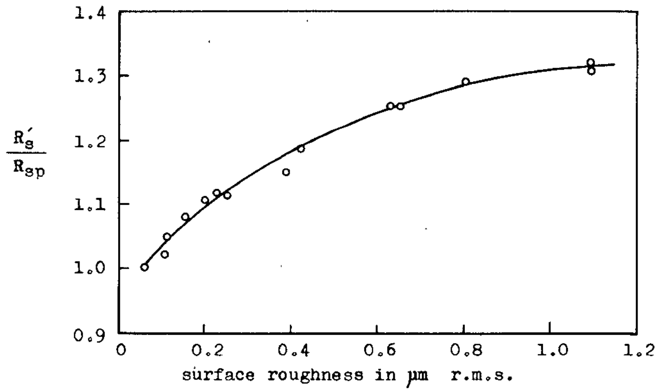


Fig. 4. Surface resistance ratio R_{sp}/R_s' versus surface roughness.

TABLE I
COMPARISON OF MECHANICAL AND PHOTOMICROGRAPHICAL ROUGHNESS DATA

Abrasive paper	Grain size	Profilometer reading, r.m.s., µm	Photomicrography r.m.s., µm
410	15	.06	.17
600	15	.15	.27
400	24	.31	.45
320	32	.57	.90
240	45	.80	1.13
120	110	1.07	1.66

the rms height variation was about equal to the skin depth (0.41 µm at 35 GHz for copper).

WAVEGUIDE ATTENUATION

The third part of the investigation involved determination of the attenuation of commercially available waveguides. Its purpose was to evaluate the validity of existing published data [1]–[3], [9]–[12] and to find relationships between the experimental attenuation figures and the more fundamental results obtained earlier.

A number of basic features of waveguide attenuation can be studied by rewriting the customary equation for the attenuation of standard rectangular waveguides [13] as a product of four terms:

$$\alpha = R_s f K F_g \text{ dB/m}$$

$$R_s = 2.52 \times 10^{-2} \sqrt{f^{GHz}/10}\ \Omega, \qquad \text{for silver}$$

$$R_s = 2.61 \times 10^{-2} \sqrt{f^{GHz}/10}\ \Omega, \qquad \text{for copper}$$

$$F_g = (\lambda/2a)[1 + (\lambda/2a)^2][1 - (\lambda/2a)^2]^{-1/2}$$

and λ is the free-space wavelength and a is the width of waveguide ($a = 2b$) measured in equal units. The first term, R_s, represents the surface resistance of the internal guide walls, which is proportional to the square root of the operational frequency. It includes a constant associated with the bulk values of the dc resistivity of silver and copper. The second term is the frequency followed by a constant K and a geometry factor F_g. The latter depends solely on the ratio of the wavelength to the internal width of the waveguide. The factor F_g remains unaltered if the frequency is increased and the dimensions simultaneously reduced in proportion to λ or $1/f$.

The equation shows that the attenuation increases for increasing frequency with $f^{3/2}$ if the cross-sectional dimensions are scaled down in proportion to λ. Plotting the theoretical attenuation of the standard waveguides for the various frequency bands clearly indicates this trend [see the dashed line in Fig. 5(b)]. It can also be concluded from the equation that, at a given frequency, the ratio of the actually measured attenuation to the theoretical value directly equals the ratio $R_{s\,\text{measured}}/R_{s\,\text{theoretical}}$ used in the other parts of the investigation as a measure of both the excess losses and the difference between measured and theoretical values of the surface resistance.

A review of published attenuation data reveals considerable discrepancies between the results of different investigators. Published experimental values of the attenuation in decibels per meter of standard waveguides made of coin silver are shown in Fig. 5(b). Included are the theoretical values and results obtained in this investigation. Discrepancies between the previously published values are probably caused by measurement errors and by different measurement conditions. Attenuation measurement errors of about ± 0.2 dB or more are not uncommon at frequencies of 70 GHz. This is indicated by recently published data [12]. Converted into excess-loss ratios, these error limits correspond to an R_s-ratio uncertainty of 1.2–1.4. Due to these uncertainties, no conclusive trends with regard to the frequency dependence of the excess losses can be derived from the published data. The review clearly indicates that very high measurement accuracies are required if conclusive and reliable data on the loss characteristics of conductors in the millimeter region are to be obtained.

In recognition of these requirements, careful experiments were conducted to find the attenuation of a number of samples of standard waveguides (WR 28, 12, 8, and 5) made of coin silver and copper. An error study showed the possibility of deviations due to the medium in the guide, in particular, at the peak of gaseous attenuation due to oxygen at 60 GHz. The effect may cause an increase of a few hundredths of one decibel per meter guide length in the attenuation. Since this is of the order of magnitude of errors caused by internal reflections (mismatch conditions) and other uncertainties, the effect was disregarded. The samples were waveguide sections, in most cases about 2 m long, in the same condition as when received from the manufacturer. To clean the guides, dry pieces of cotton threads were drawn through each. Measurements of one section of WR 12 made of silver were repeated after the guide was wet-cleaned with cotton threads, which were first dipped in potassium cyanide; rinsed, with distilled water; and then dried. This process was designed to determine the effect of chemical cleaning on the attenuation.

Special coupling elements were designed to attach two short sections of waveguide to the ends of the waveguides

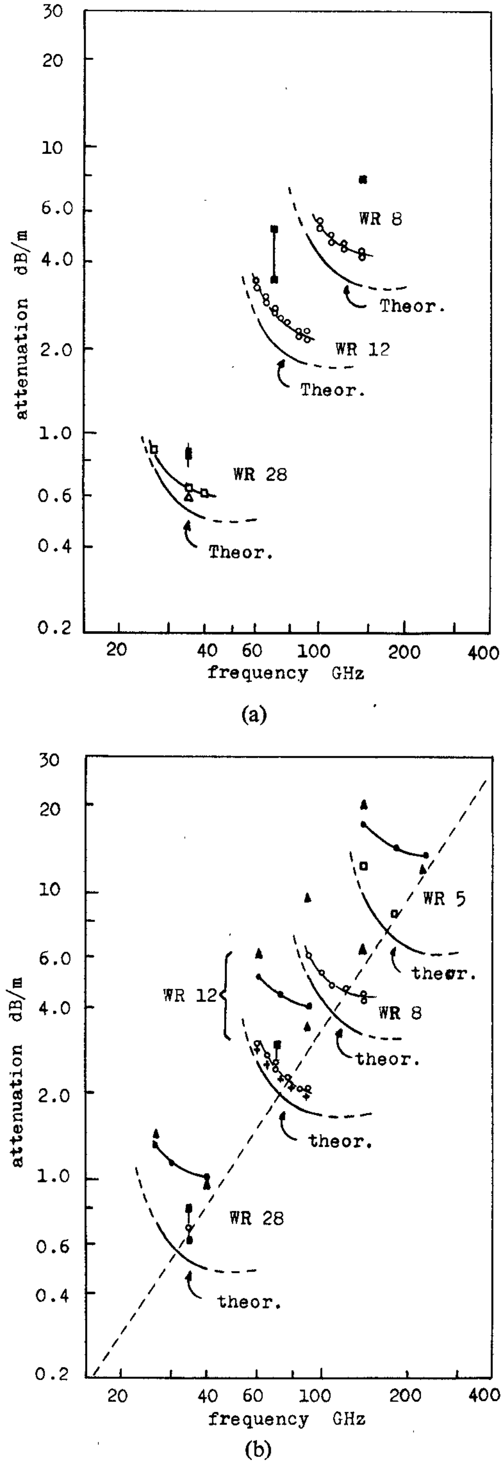


Fig. 5. (a) Measured attenuation of standard-size waveguides made of copper: ■ Benson [2], ○ Tischer, □ Tischer, values calculated from measured surface resistance of polished copper, △ Tischer [4], value calculated from measured instrinsic surface resistance. (b) Measured attenuation of standard-size waveguides made of coin silver: ▲ Baytron [11], ● Wharton [9] and Hitachi [10], ■ Benson [2], ○ Tischer, + Tischer, after cleaning, □ Tischer, accuracy not assured.

under investigation. The attenuation of the end sections was determined first and then subtracted from the overall value. Use of these clamped-on coupling elements avoided attenuation changes caused by soldering flanges onto the waveguides.

Reflections were reduced and the matching conditions controlled by the use of isolators and additional attenuators. The measurement conditions such as matching and square-low operation of detectors were continuously tested. At fixed-frequency measurements, bolometers were used. The measurements were usually repeated using different methods each time. This allowed immediate comparisons of the results. In some cases the measurements were repeated on short sections of waveguides after cutting the long sections into two parts. The results of these measurements are shown in Fig. 5(a) and (b).

The results, in general, indicate that the attenuation of waveguides made of silver is considerably lower than suggested by previously published data. An evident trend indicates that the discrepancy between experimental and theoretical values of attenuation increases with increasing frequency. Chemical cleaning carried out in a WR 12 section made of silver reduced the attenuation by a clearly observable amount and reduced the surface resistance ratio at 70 GHz from about 1.19 to 1.14.

Conclusions

Combining the results of the various parts of this investigation allows interesting conclusions. Experiments in the first part of the project indicate that an anomalous skin effect of copper exists at room temperature and may be described by an R_s ratio of about 1.135. This anomaly represents one of the effects which cause the discrepancy between the experimental and the theoretical surface resistance. This contribution to the discrepancy is intrinsic and probably cannot be reduced by any kind of surface preparation.

The results of measurements of the surface resistance of machined and mechanically polished surfaces, carried out in the second part of the investigation, show that work hardening due to machining and surface processing increase the R_s ratio to about 1.18 for mechanically highly polished surfaces. The ratio also increases substantially with increasing roughness as can be observed by inspection of Fig. 4. For rough surfaces (one-dimensional roughness), when the peak-to-peak variation is very large in comparison to the skin depth, the R_s ratio resulting from roughness assumes a value corresponding to the area increase of the surface associated with the roughness. As an approximation it can be stated that the total R_s ratio is the product of the R_s ratios associated with the major effects such as the anomaly of the skin effect, work hardening, and roughness.

The ratios of the experimental and theoretical values of the attenuation of waveguides and Q factors of resonators and circuits equal those of the surface resistances. As a consequence of this equality, the results of this study of plane copper surfaces are directly applicable to these components. They allow valuable conclusions in practical engineering situations such as the manufacture of waveguides and their preparation during the fabrication of components, and engineering design. Recent experiments and waveguide measurements indicate that the basic effects are similar in the case of silver surfaces. The results also indicate that the R_s ratios increase with increasing frequency. The continuing investigation is expected to yield additional useful information.

Acknowledgment

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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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The authors are with the Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Musashino, Tokyo, Japan.

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