SUBMILLIMETER WAVE FREQUENCY MULTIPLIERS AND IMPATT OSCILLATORS

M. Hirayama, T. Takada, T. Ishibashi and M. Ohmori
Musashino Electrical Communication Laboratory
Nippon Telegraph and Telephone Public Corporation
Musashino-shi, Tokyo 180, Japan.

ABSTRACT

GaAs frequency multipliers up to 600 GHz and Si p^+-n-n^+ IMPATT oscillators up to 430 GHz were developed. An output power of 0.12 mW at 450 GHz was obtained by the tripler using a thin film integrated circuit and a GaAs honeycomb-type Schottky barrier diode. The IMPATT oscillator cooled by liquid nitrogen delivered 2.2 mW at 412 GHz with 0.047 % conversion efficiency.

Introduction

Short millimeter wave and submillimeter wave solid state sources are needed for use in radio astronomy, plasma diagnostics, spectroscopy, etc.. Recently, verious types of semiconductor devices, Josephson mixers and gas lasers were investigated for these purposes. In the extremely short wave region GaAs Schottky barrier diodes with small junction area have been used as a detector and mixer.[1,2] Multipliers up to 300 GHz and cw IMPATT oscillators have been reported.[3,4]

This paper presents experimental results of GaAs frequency multipliers in the 300-600 GHz region and Si p^+-n-n^+ IMPATT oscillators which operated up to 430 GHz.

Frequency Multipliers

In the submillimeter wave region it is difficult to fabricate multipliers using conventional techniques because of the extremely small fabrication tolerance. Microwave integrated circuit techniques which were used for a millimeter wave mixer[5] were applied for the multipliers reported here.

The diode package mount has a 150 GHz band waveguide (WR-7) in the input side and a 300 GHz band tapered waveguide (WR-3) in the output side. The waveguides were made as short as possible by introducing a new short piston driving mechanism to reduce propagation loss, that is, the micrometer driving the short piston moves perpendicularly to the waveguide propagation axis.

Figure 1(a) shows the inner part of the diode package. It consists of an input output waveguide, circuits on a quartz substrate ($0.34 \times 2.3 \times 0.06$ mm^3) which is attached on the ground plane of microstrip by Aron Alpha resin. The input output waveguide and microstrip enclosure were fabricated by shaving brass with a diamond bit and electroplating the surface with gold. The surface roughness was about 300 Å which is less than one fourth of the skin depth for gold at 300 GHz. In the channel which encloses a quartz substrate, 150 GHz and 300 GHz wave propagate only with a dominant microstrip mode, pseudo TEM, because the channel width is less than the cutoff width of longitudinal-section-magnetic mode and a transverse-electric-surface mode.

Figure 1(b) shows a conductor pattern of thin film integrated circuit for the multiplier. The circuits consist of a rod-type probe for transition from the waveguide to the microstrip, a dc bias circuit and 300/450 GHz band rejection filters. An optimum length of the probe which is a half height of the input waveguide was determined from a scaling experiment at 10 GHz. The dc bias circuit and the band rejection filters were designed using quarter wavelength lines and stubs.

GaAs honeycomb-type Schottky barrier diodes were used as a variable capacitance diode for the multiplier. A Ni-Au Schottky barrier was fabricated on an n-type epitaxial layer by electroplating. Junction diameter, carrier concentration and thickness of the epitaxial layer were designed to be 1.5 μm, $2.5 \times 10^{17} cm^{-3}$ and 0.3 μm, respectively. The calculated cutoff frequency of the fabricated diode is 4400 GHz at the breakdown voltage. A diode chip was inserted into the lower side of the output waveguide and one of the honeycomb junction was connected to a platinum whisker with a 10 μm diameter under a microscope.

Impedance matching is one of the most important design factor on microwave devices. In the submillimeter wave region, we do not have effective means such as an E-H tuner in millimeter wave region. The impedance matchinq on the multiplier was made by selecting a diode junction diameter (1.5 μm), characteristic impedance values of the input microstrip (65 ohm) and that of the reduced height output waveguide (168-149 ohm in the 300-450 GHz). If an input impedance matching circuit are needed, we could put it on the quartz substrate.

Performance of the multiplier was measured as follows. A 150 GHz band high power IMPATT oscillator was used as an input power source. Output powere was measured with a commercial thin-film thermo-couple calibrated by a dry calorimeter. Output frequency was calculated from a guide wavelength measured by a W-Si point contact diode with a movable sliding short, and was verified with cutoff waveguide test section. For tripler and quadrupler operations, a cutoff filter was connected to the output waveguide flange, because the diode package was desiged originally for a doubler. Sliding short pistons in an input and an output waveguide were used for circuit tuning.

The output power of the doubler was -1.8 dBm at an input power level of 11 dBm with a conversion loss of 12.8 dB at 300 GHz.

The output power and conversion loss versus input power of the 450 GHz band tripler is shown in Figure 2. A maximum power of -9.3 dBm which is equal to 0.12 mW was obtained.

600 GHz band quadrupler output was detected at the power level of about 1 μW which is enough for a local oscillator of a Josephson mixer. Figure 3 shows the detector output voltage versus sliding short position. The guide wavelength corresponds to 601.2 GHz.

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IMPATT Oscillators

In the submillimeter wave region, several effects such as ionization rate saturation, carrier diffusion, series resistance, velocity modulation, etc., degrade IMPATT oscillation performance. Among them the finite avalanche build-up time, due to the ionization rate saturation at high electric field, makes the design of fundamental mode submillimeter wave IMPATTs essentialy difficult. Frequency characteristics of a calculated negative resistance of a IMPATT diode has a peak at the fundamental oscillation frequency and the negative resistance value decreases below the diode series resistance value above 200 GHz. For this reason the higher-harmonic mode operation is considered preferable rather than the fundamental mode.

Moreover cooled IMPATT operation is effective for an improvement of the diode performance, because of a saturation velocity.[6] Calculated values of the small-signal negative resistance show a shift in optimum frequency to a higher value with decreasing operation temperature.

Si p^+-n-n^+ diodes with depletion layer width of 0.15 μm at breakdown voltage of about 7.5 volt were fabricated. The impurity profiles in the epitaxial layer of n^- on n^+ substrate is shown in Figure 4. The 0.05 μm thick p^+ layer was formed by thermal diffusion of boron at 900 ^oC for 4 minutes. Then the n-layer was made by ^{31}P ion-implantation with multiple acceleration energies to obtain a uniform donor density. Acceleration energies of 55, 105 and 205 keV were applied for Q-series diodes. The annealing was made at 850 ^oC for 10 minutes. The diode thickness was made below 5 μm to reduce the series resistance. Metal layers of Ti (500 Å) and Au (1 μm) were used for ohmic contact. The diode pellet was thermo-compression bonded on a gold plated copper heat sink and was connected to a quartz stud by a gold ribbon. Diode diameter was optimized experimentally around 20 μm.

RF measurements were performed in continuous wave operation at room ambient and at liquid nitrogen temperature. The diode was mounted in full height WR-4 waveguide cavity with an adjustable short piston. In cooling the diode, the mount was contacted to a liquid nitrogen vessel wall in vacuum as shown in Figure 5. Output power was delivered to outside through a gold plated adiabatic waveguide made of cuplic nickel. The short piston was driven from outside of the vessel. A high pass filter was inserted at an output port of the oscillator for harmonic operation.

Figure 6 shows performance of cooled operation compared with room ambient oscillation in the 200-400 GHz region. Frequencies were raised by an amount of 10-20 % compared to the room temperature operation and these shifts correspond to the electron saturated velocity increase of about 20 %.

Figure 7 shows the output powers obtained in our laboratory in the 200-600 GHz region. IMPATT output power at room ambient is measured up to 400 GHz. Cooled IMPATT power was 2.2 mW with conversion efficiency of 0.047 % at 412 GHz. Multiplier delivers more power than IMPATT oscillator above 350 GHz.

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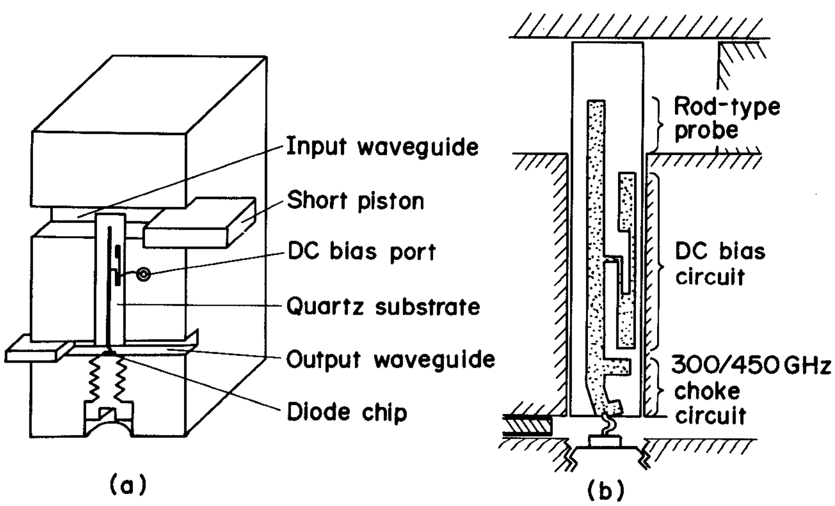

Fig.1. Multiplier structure; (a) Inner part of the diode package, (b) Top view and design of integrated circuit.

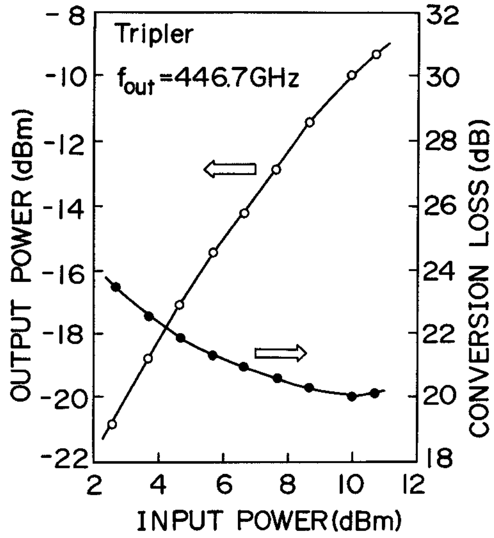

Fig.2. 450 GHz band tripler performance.

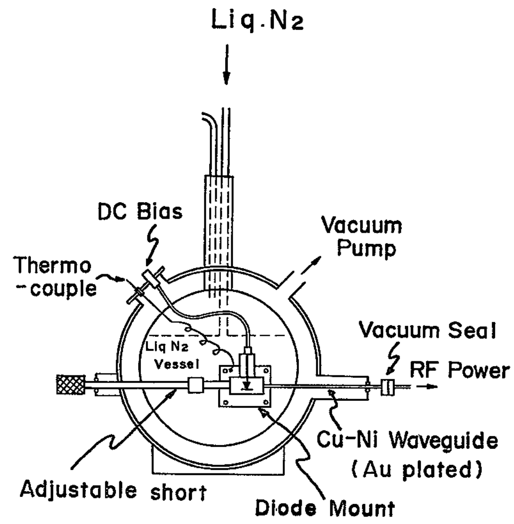

Fig.5 Inner view of cooled IMPATT diode mount.

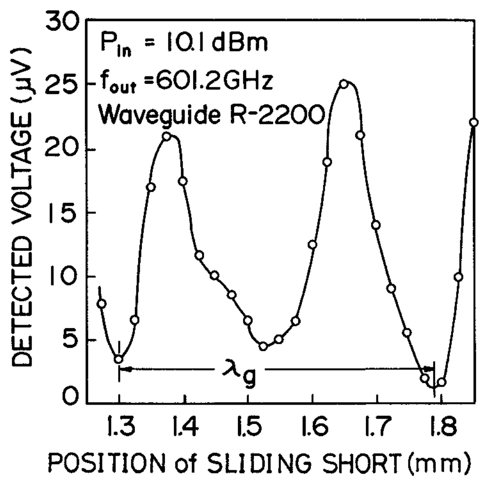

Fig.3. Detected voltage with sliding short position at 600 GHz quadrupler operation.

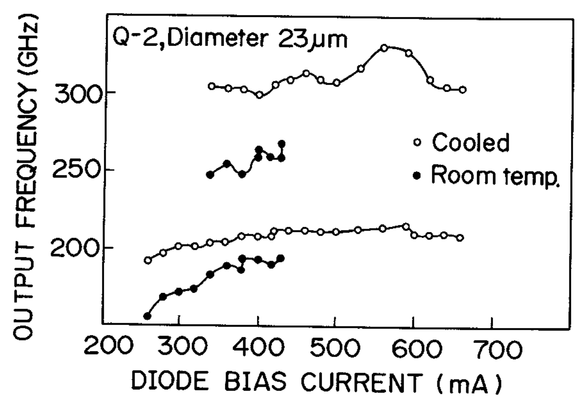

Fig.6. Oscillation frequency variation for room temperature and cooled operation.

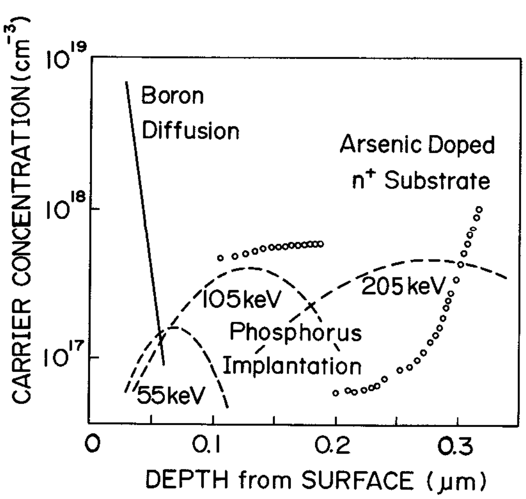

Fig.4. Impurity profile of Si p^+-n-n^+ IMPATT diode.

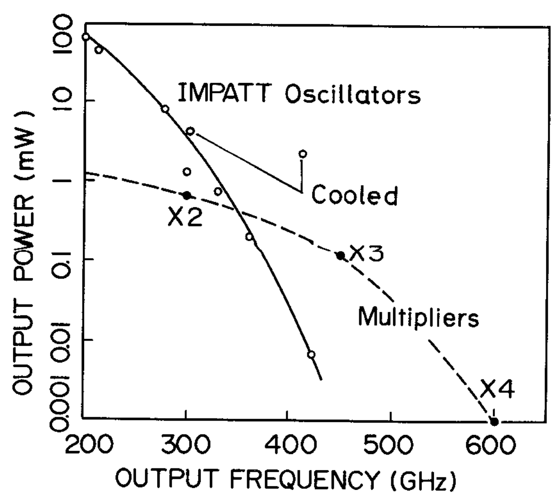

Fig.7. Output powers of IMPATT oscillator and multiplier in the 200-600 GHz region obtained in our laboratory.