Topics in Millimeter Wave Technology

VOLUME 2

Edited by
Kenneth J. Button

TOPICS IN MILLIMETER WAVE TECHNOLOGY

VOLUME 2

This page intentionally left blank

TOPICS IN MILLIMETER WAVE TECHNOLOGY

VOLUME 2

Edited by *KENNETH J. BUTTON*

NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS

ACADEMIC PRESS, INC.
Harcourt Brace Jovanovich, Publishers
Boston San Diego New York
Berkeley London Sydney
Tokyo Toronto

ACADEMIC PRESS, INC.
1250 Sixth Avenue, San Diego, CA 92101

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
24–28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Topics in millimeter wave technology.

Includes bibliographies and index.
1. Millimeter wave devices. 2. Wave guides.
I. Button, Kenneth John.
TK7876.5.T67 1987 621.381'331 87-17583
ISBN 0-12-147699-5 (vol. 1)
ISBN 0-12-147700-2 (vol. 2)

88 89 90 91 9 8 7 6 5 4 3 2 1

Printed in the United States of America

CONTENTS

CONTRIBUTORS

Numbers in parentheses indicate the pages on which authors' contributions begin.

D. L. BROWER (83), *Princeton Plasma Physics Laboratory, Princeton University, PO Box 451, Princeton, New Jersey 08544*

DENISE A. BROWN (47), *NYNEX Information Resources, Lynn, Massachusetts 01901*

N. C. LUHMANN (83), Jr., *Princeton Plasma Physics Laboratory, Princeton University, PO Box 451, Princeton, New Jersey 08544*

KAORU MOTOYA (1, 213), *Semiconductor Research Institute, Kawauchi, Sendai 980, Japan*

JUN-ICHI NISHIZAWA (1, 213), *Research Institute of Electrical Communication, Tohoku University, Sendai 980, Japan*

E. OTSUKA (173), *Department of Physics, College of General Education, Osaka University, Toyonaka, Osaka 560, Japan*

H. K. PARK (83), *Princeton Plasma Physics Laboratory, Princeton University, PO Box 451, Princeton, New Jersey 08544*

W. A. PEEBLES (83), *Princeton Plasma Physics Laboratory, Princeton University, PO Box 451, Princeton, New Jersey 08544*

MARTIN V. SNEIDER (47), *AT&T Laboratories, Crawford Hill Laboratory, Holmdel, New Jersey, 07733*

This page intentionally left blank

CHAPTER 1

The CW GaAs TUNNETT Diodes

Kaoru Motoya

Semiconductor Research Institute
Kawauchi, Sendai 980, Japan

Jun-ichi Nishizawa

Research Institute of Electrical Communication
Tohoku University
Sendai 980, Japan

ISBN 0-12-147700-2

I. Introduction

A semiconductor coherent signal source, such as the TUNNETT diode over 100 GHz to 1 THz (1000 GHz), has been eagerly desired for many application fields, since the IMPATT diode oscillator can not be used for the local oscillator because of its high noise and the backward wave oscillator (Carcinotron), which is a vacuum tube. The IMPATT diode oscillator has drawbacks such as a short lifetime, the need for a high voltage power supply (over 1000 V) and its large volume, including the power supply, compared to those of the semiconductor devices.

The GaAs TUNNETT diodes, which were developed by the junior author's group in the early 1950s, was introduced in Chapter 4 in Vol. 5 of this series (Nishizawa, 1982), as were the Raman semiconductor (Nishizawa, 1963, Pidgeon et al., 1971, Nishizawa and Suto, 1980) and Brillouin lasers (Suzuki et al., 1977). Far infrared generation was introduced in Chapter 6 in Vol. 7 of *Infrared and Millimeter Waves* (Nishizawa and Suto, 1983).

The avalanche multiplication phenomenon in a semiconductor has been found by the junior author (Watanabe and Nishizawa, 1952), McKay and McAfee (1953), and Gunn (1956).

The transit time negative resistance diode was proposed independently by Nishizawa and Watanabe (1953), by Shockley (1954) and by Read (1958) as a solid-state microwave source. The TUNNETT diode was proposed by Nishizawa and Watanabe (1958) as the result of analysis of the avalanching negative resistance diode which is called the IMPATT diode today.

The superiority of the TUNNETT diode to the IMPATT diode by virtue of the high frequency, low noise, and low bias voltage has been confirmed experimentally using GaAs p^+-n diodes by the J. Nishizawa's research group since 1968 (Okabe et al., 1968). At that time the existence of the TUNNETT, IMPATT and the hybrid of the TUNNETT and IMPATT modes had been determined in the course of study (Okabe et al., 1968).

The pulsed submillimeter wave oscillation of 338 GHz ($\lambda = 0.89$ mm) with 10 mW output power has been realized from GaAs p^+-n-n^+ diode (Nishizawa et al., 1979). Since then, the GaAs p^+-n^+-$i(\nu)$-n^+ has been developed in order to raise the efficiency over the p^+-n-n^+ diode by our group (Nishizawa et al., 1981, 1984).

Recently the performance limit of the IMPATT has been recognized by other workers (Elta and Haddad, 1979). The hybrid mode diode, which was named MITATT (mixed tunneling and avalanche transit time), has been developed as a CW source at 150 GHz by Elta et al. (1980); this is the first successful achievement of CW operation. This was made by the GaAs Schottky barrier diode.

It is worth mentioning here that the efficiency of tunneling and the stability for the lifetime in a *p-n* junction will be superior to that in a Shottky barrier diode, as already pointed out by Nishizawa (1976).

The poor oscillation performances from GaAs Schottky barrier type (p^+-n^+-n-n^+ diode) TUNNETT (Ohmi and Motoya, 1976) verified the above mentioned prediction with the comparison of the GaAs *p-n* junction type TUNNETT diode (Okabe et al., 1968, 1969, Nishizawa et al., 1974, Nishizawa, 1975, Nishizawa et al., 1977b, 1978a, 1978b, 1979, 1980, 1984).

Hence the research effort to realize the GaAs *p-n* junction type CW TUNNETT is thought to be valuable for many practical application fields. The object of this chapter is to present recent progress of the GaAs hyperabrupt p^+-n^+-$i(\gamma)$-n^+ TUNNETT diode. The superiority of the TUNNETT over the IMPATT and MITATT diode is also described.

II. Theory of TUNNETT Diode

A. TUNNETT Diode

The proposal of the TUNNETT diode was presented in the study of the avalanching negative resistance diode which included the diffusion effect by Nishizawa in 1958 (Nishizawa and Watanabe, 1958).

The importance of the buildup time of the avalanche injection and its spatial distribution was pointed out to determine the higher frequency limit in the IMPATT diode. This concept was developed as the avalanche induced dispersion effect by detailed numerical calculations by Nishizawa (Nishizawa, 1971, 1974, Nishizawa et al., 1974, Nishizawa et al., 1978c). The oversimplified approximation of the avalanche injection was corrected by Misawa (1966), but he did not give any physical explanation about a large effect of the time constant in the avalanche injection.

The importance of the above effect was recognized later by another researcher. The diffusion-aided spreading of the injected current pulse and the diffusion were published by several authors since 1970, after the theory was proposed by Nishizawa in 1958 (Kuvås, 1970, Gupta et al., 1975 and Schwarz, 1977). The GaAs p^+-n TUNNETT, IMPATT and MI-

TATT diodes were experimentally realized by the authors' group after 1968.

However, the millimeter wave GaAs IMPATT and MITATT diodes have poor oscillation frequency performances compared to those of GaAs TUNNETT and Si IMPATT diodes to date (Gibbons et al., 1972, Nawata et al., 1974, Schwarz and Bonek, 1978, Elta et al., 1980, Chang et al., 1981).

The influence of the tunnel injection in the transit time negative resistance diode has been presented by several authors, not including our group, after the realization of GaAs TUNNETT diode by our group since 1968 (Semichon et al., 1970, Kwok and Haddad, 1972, Chive et al., 1975, Elta and Haddad, 1978, 1979a, 1979b, Pan and Lee, 1981a and 1981b, Allen et al., 1982).

The many limitations, in the short millimeter to submillimeter wave region, of the transit time negative resistance diode, such as series resistance with decreasing device area, skin depth, the matching problem from this kind of diode to the output load and thermal resistance, are common difficulties in producing higher frequency and higher output power with a high efficiency. Their limits are common to other diodes, such as detector, mixer and varactor diodes, for short millimeter to submillimeter wave regions.

B. Small Signal Analysis of TUNNETT Diode (Okabe and Nishizawa, 1969)

The simple model of the TUNNETT diode is used, so that the voltages of the injection and transit time region are constant. The small signal analysis of the TUNNETT diode has been carried out. Fig. 1 shows the

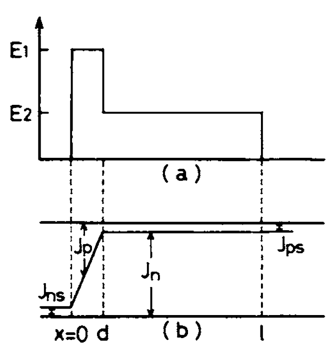

FIG. 1 (a) The electric field profile and (b) the distribution of electrons and holes in the Read-Nishizawa type TUNNETT diode.

electric field profile and the current distribution in DC condition of the Read-Nishizawa type TUNNETT diode.

C. Injection Region

Next assumptions are made that

(1) the uniform avalanche and tunnel injection under the constant electric field intensity.
(2) the saturation velocity $|v_n| = |v_p| = v_s$ for the carriers, and
(3) the neglect of the diffusion effect of carriers.

If the uniform electric field is assumed, the solving way is same as that the *p-i-n* diode analyzed by Misawa (1967). The basic equations are given by;

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon}(N_D - N_A + p - n) \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + g \tag{2}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + g \tag{3}$$

and

$$J_n = -qvn \text{ and } J = -qvp. \tag{4}$$

When the uniform tunneling condition is satisfied, then

$$g = A\gamma(E) \tag{5}$$

where $\gamma(E)$ is the tunneling probability and A is the constant, respectively. The boundary conditions for $\tilde{J}_n(0)$ and $\tilde{J}_p(d)$ are given as

$$\tilde{J}_n(0) = J_{ns} \text{ and } \tilde{J}_p(d) = \tilde{J}_{ps}.$$

However, these primary currents can be neglected since the primary currents of the tunnel injection do not play as important a role as the avalanche injection.

The admittance Y is given by $\tilde{J}_n$ is divided by $\tilde{V}(d)$ and is plotted in Fig. 2. The tunneling layer width 400 Å and, $f_0 = 400$ GHz are chosen for the parameters in the calculation. The vector of the injection current does not rotate as quickly as in case of the avalanche injection. The phase delay of the injection current to the applied voltage and the attenuation of the amplitude of the injection current are small to the range of several hundreds GHz.