THE GaAs TUNNETT DIODES

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ABSTRACT

The Tunnel injection transit time (Tunnett) diode operates in higher frequency region and with lower noise level than that of the Impatt diode. In thin carrier generating region, the tunnel injection which depends steeply on the electric field intensity over 1000 kV/cm, where the ionization of carriers can be neglected, leads to the higher efficiency operation of the Tunnett than that of the Impatt. GaAs Tunnett diodes with p^+n and p^+nn^+ structure have been fabricated by a new LPE method (TDM under CVP). The fundamental oscillation at the frequency from about 100 GHz up to 248 GHz has been obtained from the p^+nn^+ diode.

Introduction

At higher frequency region the thickness of the avalanche injection region becomes relatively thicker in the whole thickness of the diode and it finally occupies the whole depletion layer, since the ionization coefficient of an electron and a hole has saturated and accordingly the thickness to obtain enough generation of carriers has limited till a certain minimum thickness even with high field below tunneling field intensity.

The Tunnett (tunnel injection transit time) diode was proposed and evaluated by J. Nishizawa and Y. Watanabe in 1958.[1] The conception of this diode was introduced in the analysis of the high frequency properties of the avalanching negative resistance diode, which is called the Impatt diode nowadays. The upper limit of the oscillation frequency of the Impatt diode is determined by the avalanche multiplication phenomenon itself. On the other hand, recently the fundamental properties of the avalanche multiplication phenomenon has been analyzed and clarified as the avalanche induced dispersion effect,[2] which seems to explain the lower efficiency and lower transit angle expected from the ideal operation predicted from former theoretical analysis of the real Impatt diode.[3] Based on theoretical analysis considering dispersion, region of the transit time negative resistance (TTNR) diode should be much more thinned than that estimated from simple former theory, in order to obtain the higher oscillation frequency.

On this viewpoint, the tunnel effect is suitable and in the same time, of its own accord, becoming to play a main role for the injection mechanism in the range from short millimeter to submillimeter wave. The tunnel injection is dominant even at lower field over 1000 kV/cm in approximately 100 Å thickness in a reverse biased pn junction and is much convenient because of its lower noise level and lower bias voltage than that of the Impatt diode.

The Tunnett diode was confirmed experimentally in 1968 by the author's group[4] and has been developed.[5,6,7] This paper describes the recent results of the GaAs Tunnett diodes oscillating up to 248 GHz.

Theory

The simple operation principle of the Tunnett diode is illustrated in Fig. 1. The maximum injection occures at $\pi/2$ radian, but it can be controlled larger than $\pi/2$ radian with the use of the charging up time constant of the carrier generation region in the actual operation. This means that the concentration of the field intensity into tunnelling region needs some time to ionize the impurities in the depletion layer of the tunnel junction. Roughly speaking, the injected carriers in the Tunnett diode flowing in the transit angle from π to 2π radian. The main features of the Tunnett diode are summarized in Table 1. The f_{max} of the fundamental oscillation frequency has been estimated about 1000 GHz. The upper limit of the oscillation frequency of the TTNR diode is determined by the diffusion process in the transport process of the injected carriers.[1] The requirements for materials are the higher injection efficiency and the higher saturation velocity and the lower diffusion coefficients of an electron or of a hole.

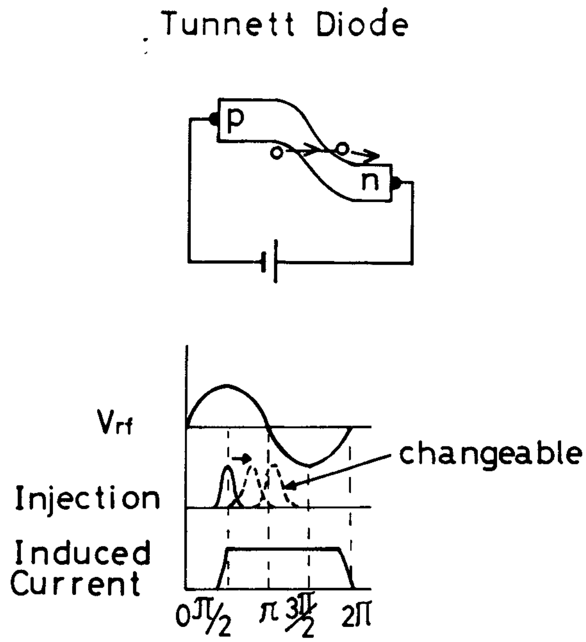


Fig.1 Operation Principle of the Tunnett Diode

f_{max} of the fundamental oscillation frequency(GHz)	~ 1000GHz	Si ; 300GHz GaAs ; 100GHz
Electric field intensity (kV/cm)	>1000	<1000
Bias voltage	small	higher than the Tunnett
Noise level	small	high
Temperature coefficient	negative	positive

Table 1 Main Features of Tunnett Diodes Compared with Impatt Diodes

Various structures of the Tunnett diode such as a reverse biased pn structure, a reverse biased Schottky barrier (SB) structure or a metal-insulator semiconductor (MIS) structure has been proposed. Among them a pn structure is superior one, since the tunnel injection efficiency and the thermal stability are higher than others. The precise control of the doping profile at the injection and the lower series resistance are the key points for the realization of the Tunnett diode, so the elaborate techniques for the device fabrication are necessary.

State of the Art of the Some TTNR Diode Compared with the Tunnett Diode

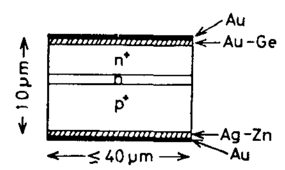
In case of the Barritt diode its upper limit is determined by the time delay in diffusion process of the minority carrier until it reaches to the drift region, so the f_{max} is approximately 30 GHz. The GaAs Impatt diode is inferior to the Si Impatt above about 50 GHz, since the ionization coefficients of carriers are smaller than that of Si. The GaAs Impatt which operates in higher efficiency in the X band compared with the Si Impatt will be attributed to the cooperation with the Gunn effect (Gunnpatt mode).[8] Recently detailed oscillation experiment of Si Impatt operated up to 400 GHz with fifth harmonic mode has been reported that the fundamental oscillation ranges from 30 to 90 GHz.[3]

Compared with the diodes mentioned above the GaAs Tunnett diode exhibits the fundamental oscillation frequency from about 100 GHz up to 248 GHz in our experiments.

Device Fabrication of the GaAs Tunnett Diode

The GaAs Tunnett diodes have been fabricated by the new LPE method, that is the temperature difference method under controlled vapor pressure (TDM under CVP).[9] The n- or n-n^+-type layer are grown onto the (100) Zn doped p^+-type substrate (ρ : 4 ~ 6 x $10^{-3}\Omega$ cm) and the growth temperature ranges from 600 to 700° C in order to prevent Zn diffusion into the n-type layer.

The structure of a p^+nn^+ diode and the properties of the epitaxially grown wafers are shown in Table 2.



Diode Structure	Growth Temperature (°C)	Doping Density of n layer (cm^{-3})	Doping Density of n^+ layer (cm^{-3})	Thickness of n layer (µm)
p^+n	600 - 670	5-10 X 10^{17}	——	1 - 2
p^+nn^+	640 - 650	1 X 10^{18}	>3 X 10^{18}	0.7 - 3

Table 2 Structure of the p^+nn^+ Diode and the Properties of the Epitaxially Grown Wafers

Static Characteristics

Prior to the oscillation experiment, the static characteristics of the CV and the IV are measured.

The CV measurement shows that the abrupt distribution has successfully formed in the junction. The IV characteristic shows that the diode with $N_D \simeq 5 \times 10^{17}$ cm^{-3} has slightly negative or no temperature dependence in the junction region and the diodes with $N_D \gtrsim 8 \times 10^{17}$ cm^{-3} have negative temperature dependence. These results coincide with our previous results.[4]

Oscillation Experiment

The conventional quartz stand-off structure diode is mounted into the T-band (110 ~ 170 GHz), G-band (140 ~ 220 GHz), Y-band (170 ~ 260 GHz) or D-band (220 ~ 325 GHz) full size rectangular waveguide cavity, and the oscillation frequency has been adjusted by changing the external circuit condition not to the extraction of the harmonics. The diodes have been driven by a current pulse (50 ~ 100 nsec and 50 ~ 100 Hz).

The oscillation characteristics are tabulated in Table 3.

Diode Structure	Doping Density of n layer (cm^{-3})	β	V_{th} (V)	f_{max} (GHz)	E_{max} (kV/cm)
p^+nn^+	1 X 10^{18}	negative	-6.8 ~ -7.9	248	1600~1800
p^+n	5 X 10^{17}	≈ 0	-6.5 ~ -7.8	130	≈ 1150
	8 ~ 10 X 10^{17}	negative	-7 ~ -10	188	1400~1500

β; Temperature coefficient in I-V characteristic

V_{th}; Threshold bias voltage for the oscillation

Table 3 Parameters of the Oscillated Diodes

With increasing the electric field intensity, the oscillation frequency increases. The relations between the bias current density (J_{dc}) and the oscillation frequency of the p^+nn^+ diode are shown in Fig. 2. At the beginning, the oscillation frequency increases monotonically with J_{dc} and the wide tunning characteristics are observed up to 248 GHz. The lowest pulsed input power and J_{dc} of the p^+nn^+ diode are 2.1 W and 8 x 10^4 A/cm^2, respectively.

Conclusion

The GaAs Tunnett diodes have been fabricated by a new LPE method (TDM under CVP). The fundamental oscillation frequency up to 248 GHz has been obtained by varying the external circuit condition. Much higher oscillation from the Tunnett diode will be available with future improvement which includes a material and the doping profile of the diode.

Acknowledgement

The authors wish to thank Messers. Y. Takahashi, M. Iida, M. Sugawara and K. Shibuya for the manufacturing cavities and parts of oscillator circuits.

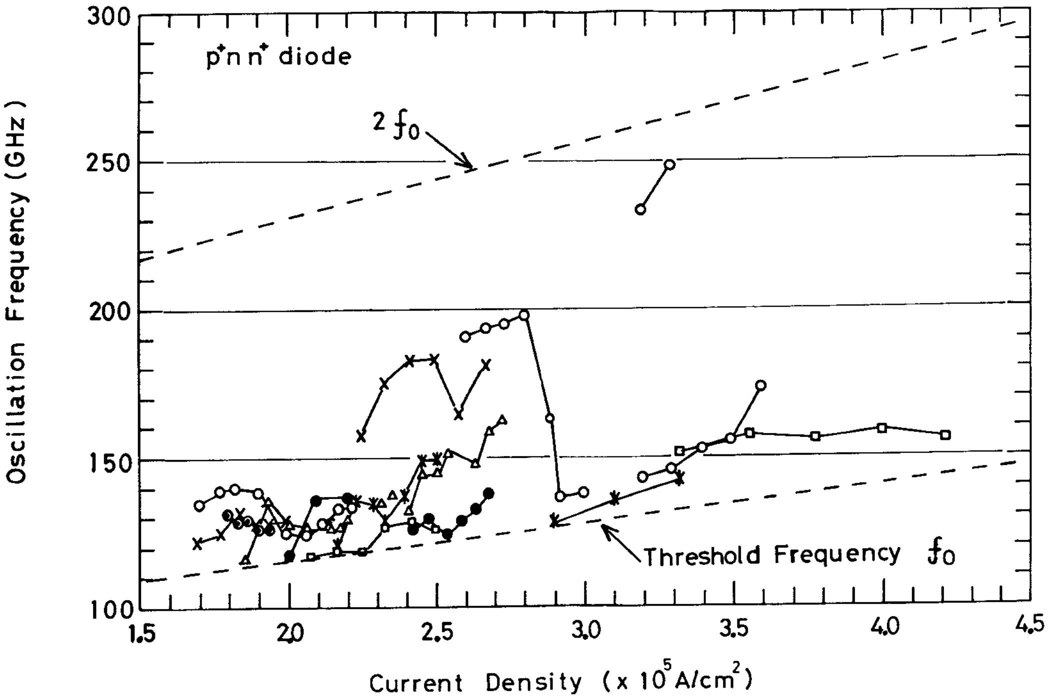


Fig. 2 Oscillation Frequency versus Current Density.

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