VI-1 RECENT ADVANCES IN BULK SEMICONDUCTOR MICROWAVE DEVICES IN JAPAN

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1. Introduction

Recent achievements and state-of-the-art in the bulk semiconductor microwave devices in Japan will be described. The discussions will be limited to GaAs Gunn oscillators unless otherwise stated. Devices other than Gunn oscillators will be discussed in the final section.

2. Fabrication Technology, Frequency and Power

H. Murakami, K. Sekido et al. (Nippon Electric Company; NEC) have developed GaAs $n^{+}-n-n^{++}$ structure for Gunn oscillators using epitaxial and liquid regrowth techniques. The n-layer (active layer) is epitaxially grown on a n^{+}-substrate using Ga as the source and ($AsCl_3$ + H_2) as the carrier gas. The lowest doping density being obtained is $5 \times 10^{14} cm^{-3}$. The n^{++}-layer is formed by using the liquid regrowth method. From samples having 10~20 μm active layer thickness, 10~100 mW for 8~12 Gc/s and 5~10 mW for 24 Gc/s have been obtained with 0.6~3% efficiency. Life test has been continued for more than 700 hours with no change in performance.

Although the epitaxial method is excellent for obtaining thin samples to be used for mm-wave oscillators, it is difficult at present to lower the doping level below the above-mentioned value. R. Nii et al. (Electrical Communication Laboratories, Nippon Telephone and Telegraph Public Corporation; ECL) is developing a new sample fablicating technique using the liquid (Sn) regrowth method to form n^{++}-layers on both sides of a sample. It has been demonstrated that by measuring the resistance of the sample throughout the regrowth process and controlling the temperature precisely, one can get an excellent control of the remained n-layer thickness and flat ohmic contacts. Figure 1 shows how the thickness of the remained n-layer (active layer) is reduced in temperature cycles. The ordinate V denotes the voltage across the sample to which a constant current (2 mA) is fed for the continuous resistance measurement.

3. Spectral Purity

The measured FM noise of a Gunn oscillator is usually higher (by 10~20 db) than that of a typical reflex klystron. As this might be a fatal drawback in its future applications to communication, the spectral purity and associated noise phenomena have been investigated in several organizations. Recently, N. Miyamoto et al. (ECL) reported a fairly good noise-to-carrier power ratio with a boat-grown sample as shown in Table I. In this table f denotes the frequency separation from carrier, N the SSB FM noise power in 1 kc/s bandwidth, and C denotes the carrier power. The best N/C ratio obtained with an epitaxially

f	$(N/C)_{FM}$	
	boat-grown sample (5 Gc/s, ECL)	epitaxially grown sample (9 Gc/s, NEC)
100 kc/s	−85 db	−73 db
400 kc/s	−93 db	−87 db
1 Mc/s	−100 db	−

Table I. Measured FM noise of Gunn oscillators.

grown sample by H. Murakami, K. Ayaki et al. (NEC) is also shown in Table I. It is considered that little more improvement in the FM noise is required to enable Gunn oscillators to be used in standard Japanese FDM-FM microwave repeaters accomodating 960 or 1800 channels. The possibility of the use in PCM-PM or PCM-AM systems is also discussed.

N. Miyamoto (ECL) also reported that when a Gunn oscillator is operating in the resonant cavity mode, the FM noise sometimes shows a decrease at a frequency near the intrinsic (transit-time) frequency, and a cavity-pulled operation at frequencies $\pm 10\%$ deviated from it gives 10 db deterioration in the (N/C) ratio.

As for the frequency stability for a longer time range, Y. Sawayama (Toshiba Electric Company) observed 3 kc/s r.m.s. frequency fluctuation for 10 minutes with a free-running Gunn oscillator in 1.6 Gc/s band.

4. Locking Experiments

Figure 2 shows the locking frequency range $2\Delta f$ vs. locking power ratio obtained by Y. Sawayama (Toshiba). The solid line shows the relation given by the locking equation: $f/f_o = (P_i/P_o)^{1/2}/Q_{ext}$, where f_o is the oscillator frequency, P_i the locking power, P_o the oscillator power, and Q_{ext} the external Q-factor of the cavity. The measured Q_{ext} was 52, whereas the solid line is drawn for $Q_{ext} = 62$. The minimum observed locking gain was 48 db.

Experiments of the subharmonic locking have been reported for an IMPATT, but not for a Gunn oscillator.

5. Parallel Operation

It is considered that in the future communication use, parallel operation of two or more samples will be needed in many cases to obtain the required power. R. Nii's group (ECL) is investigating the various phenomena that take place when the samples are not identical in their performance. It has been found that (1) the frequency is apt to be locked to that of the sample having higher output power, (2) the resultant power is almost equal to the sum of those from the samples operating independently, and (3) no appreciable increase of noise is observed when the frequency difference is within several percent of the oscillating frequency.

6. Analysis of Operation

A dynamic computer analysis including the effect of the external circuit has been performed by Y. Sawayama (Toshiba). The highest power efficiency ever obtained through his computer simulation is about 10%. This value is obtained when the bias voltage is about twice the threshold value, and the load conductance g_L and susceptance b_L are adjusted to their optimum values; $g_L \cong (1/10)g_o$ and $b_L \cong -2\omega C_o$, where g_o and C_o denote the low-field sample conductance and sample capacitance, respectively, and ω the oscillating frequency. It has also been demonstrated that the oscillator frequency can be pulled by the external circuit continuously from 0.4 f_i through 2.0 f_i, where f_i is the intrinsic frequency of the sample.

The nature of the steadily propagating high-field domain has been investigated by T. Okoshi (University of Tokyo) through a computer analysis. His data on the domain width, field and carrier-density distributions, excess voltage and excess velocity are used, together with the data obtained by Sawayama's dynamic analysis, in the efforts to establish simpler physical models of oscillation mechanism described in the following paragraph.

To obtain a general insight into the oscillation mechanism, S. Okamura's group and H. Yanai's group (University of Tokyo) are endeavoring to establish simpler but reasonably accurate models for various modes of operation. Okamura's group has proposed a simple model of oscillations at harmonic frequencies of f_i, which shows good agreement with experiments. Yanai's group has proposed a simple model explaining the measured load characteristics of the triggered cavity mode.

Efforts toward the complete understanding of the operation are also made through experiments under simplified conditions. H. Murakami, K. Sekido et al. (NEC) reported the measurement of the current waveform in a short-circuited Gunn oscillator in various ambient temperatures ranging from $-65^{o}C$ through $+96^{o}C$, and demonstrated that the waveforms show good agreement with theory. Examples of their measured waveforms are shown in Fig. 3.

7. Negative Resistance Small Signal Operations

Theoretical works by J. Koyama (ECL), A. Sasaki et al. (Kyoto University) and Y. Suematsu(Tokyo Institute of Technology), and impedance measurements by T. Tsukada (University of Tokyo) can be mentioned. However, the details will be omitted in this paper, since the use of Gunn oscillator as a small signal negative resistance device is not considered to be promising.

8. Devices Other Than Gunn Oscillator

J. Koyama, M. Sumi et al. (ECL) are working on the design theory of a traveling-wave type amplifier consisting of a GaAs bulk and a miniature slow wave structure coupled to it. No experimental scheme, however, has been proposed so far.

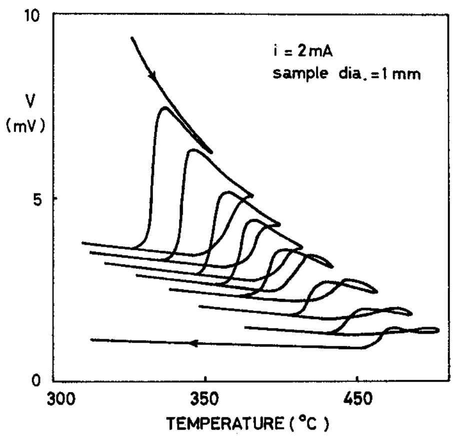

FIG. 1

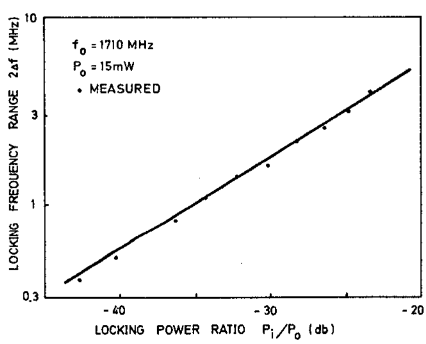

FIG. 2