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IMPROVED PERFORMANCE OF FUNDAMENTAL AND SECOND HARMONIC MMW OSCILLATORS THROUGH ACTIVE DEVICE DOPING CONCENTRATION CONTOURING

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ABSTRACT

The overall performance of mmW Gunn oscillators operating in their fundamental and second harmonic modes has been significantly enhanced as a result of several active device design improvements. The effects of altering the active layer doping concentration are compared with standard $n^{++}nn^{+}$ flat profile GaAs Gunn structures. The standard integral heat sink (IHS) process was used to permit substrate thinning to the extent that overall device thickness was reduced to 10 µm nominally. Profile tailoring to minimize temperature gradients and to permit device operation in the more efficient heat sink-anode configuration resulted in an output power of 325 mW near 34 GHz with 6.6 percent efficiency. An output power of 90 mWat 2.75 percent efficiency was achieved at the second harmonic frequency near 68 GHz.

INTRODUCTION

Conventional GaAs mmW Gunn devices have $n^{++}nn^{+}$ layers sequentially grown on a low resistivity n^{++} substrate. In most cases the n-active layer concentration is, essentially, uniformly doped. For these devices greater output power and efficiency can be obtained by biasing the substrate negative relative to the heat sink. In this heat sink-anode configuration, only one third as much temperature drop occurs across the device relative to the heat sink-cathode configuration [1]. It has recently been shown [2] that improved performance of fundamental mode GaAs oscillators results when the device active layer doping profile is intentionally altered to exactly compensate the resulting thermally induced mobility gradient under operating conditions. Using computer controlled molecular beam epitaxy (MBE), structures have been produced with various doping profiles for device opeartion in the more efficient heat sink-anode configuration. Because of the inherant relaxation effects in GaAs, its bulk small signal negative mobility vanishes near 100 GHz [3], [4]. Hence, mmW oscillators operating near 60 GHz and above depend on the harmonic mode for significant power generation [5]. The corresponding device structures require abrupt concentration changes between each epitaxial layer in order to provide harmonic rich current components. As a result of both low growth rates and substrate temperature, MBE was used to generate hyperabrupt doping concentration change and to provide fine control over the variation in layer concentration.

Epitaxial $n^{++}nn^{+}$ structures were grown on low resistivity n^{++} GaAs substrates orientated zero degrees relative to (100). Both flat and exponentially graded active region profiles were grown for fundamenatal mode operation at Ka-band (26.5 - 40 GHz) and second harmonic operation at V-band (50 - 75 GHz). In order to permit heat sink-anode (i.e., negative substrate) operation, the graded layer profiles had exponentially increasing doping toward the n^{++} contact (i.e., with negative slope, or $\alpha = n_1/n_2 < 0$, where n_1 and n_2 are the concentrations in the active region at the buffer-active and active-contact interfaces, respectively. Active devices were fabricated with gold plated integral heat sinks (IHS)[6] of 30 µm thickness. Substrates were mechanically and chemically thinned to an overall semiconductor thickness of 10-12 µm in order to minimize parasitic resistances. The best overall performance was achieved for devices having exponential grading with $\alpha<1$ operating in the heat sink-anode configuration. Most of these devices failed, as expected, when biased in the heat sink-cathode (positive substrate) mode. The best output powers measured near 31, 34 and 68 GHz were 345, 325 and 90 mW, respectively. Devices constructed with flat active layer profiles ($\alpha=1$) produced significantly lower power levels when operated in either polarity with the heat sink-anode mode providing greater output and efficiency over the heat sink-cathode mode.

Relatively few details and essentially no previous results have been reported for devices having active slope parameters $\alpha<1$ operated in the heat sink-anode configuration in either their fundamental and/or second harmonic modes. Although comparable performance has been shown for devices having an nn^{+} epi-structure (i.e., with the n^{++} contact layer omitted), with a current limiting active layer contact (CLC), only fundamental mode data has been published up through V-band operation. These devices can only be operated in the less efficient heat sink-cathode polarity. Studies of nn^{+} devices with $\alpha>1$ and having CLC's have not been reported for either fundamental or harmonic operation.

THEORITICAL DISCUSSIONS

Standard Gunn diode epitaxial structures are generally $n^{++}nn^{+}$ layers grown on low resistivity n^{++} GaAs substrates having flat doping profiles throughout the n-active region. When these devices are biased in either polarity, mobility gradients develop as a result of heat which is generated mainly within the active region. As a result, the available output power decreases. Significant improvment in overall device performance has been realized

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by designing profiles such that the resistivity ratio $\bar{\rho}/\rho_{max} = 1$ along the active region at the device operating temoerature. Further, advantage has been taken of profile tailoring to allow operation in a heat sink-anode configuration. The epitaxial $n^{++}nn^{+}$ "sandwich" structure and doping profile used in these studies is shown in Figs. 1a & 1b. The effect of selfheating, which occurs at the operating point, is shown conceptually in Fig. 1c. With the heat sink polarity positive, heat generated within the active region will be delivered to the n^{++} contact - n active interface and can induce a nearly flat resistivity profile ($\bar{\rho}/\rho_{max} = 1$) when $\alpha = n_1/n_2 < 1$. When $\alpha > 1$ the device must be biased with the substrate positive for optimum output power. Devices having $\alpha = 1$ (flat) profiles can be biased with either polarity, with negative substrate polarity being the preferred mode of operation. Measured output power for devices having $\alpha = 1$ always yielded less power than devices having $\alpha < 1$. For the optimum case of $\alpha < 1$, with the heat sink biased positive relative to the substrate, heat flows opposite the direction of conventional current flow, i.e., in the direction of electron flow. By adjusting $\alpha = n_1/n_2 < 1$ and the average value of active layer concentration, n(x), the peak to valley terminal current ratio, I_p/I_v, can be maintained near 2.0:1 at the operating point. This value is close to the highest theoretical value of 2.45:1 [7]. A high I_p/I_V ratio results in a proportionally higher value of large signal negative resistance and, correspondingly, higher output power and efficiency.

Additional factors which produce undesirable power dissipation within the active device are excessive substrate thickness, long buffer and/or contact layer lengths, as well as resistivity buffer or contact layers. The use of the IHS process allows mechanical and chemical thinning to minimize parasitic resistances (especially skin effect) resulting in an overall device thickness of 10 µm or less. It has been reported that an overall thickness of 4.5 µm has been routinely achieved in the mass production of IHS GaAs Gunn diodes for second harmonic 94 GHz operation [8]. The incorporation of an AlGaAs etch stop layer interposed within a shorter buffer layer will allow complete substrate removal and subsequent thinner overall device dimensions. Reduction of excessive internal resistances is expected to decrease the turn-on voltage to essentially its threshold value $V_T \sim 1.1$-1.5 Vdc. Practically all modern day Gunn diodes, used in the second harmonic mode, exhibit a $\Delta V = V_{op} - V_{on}$ value of 1 Vdc (or less) which can result in total loss of output power at reduced temperatures. Reduction of contact layer thickness to 0.5 µm (or less), or elimination of this layer, is expected to further improve device turn-on charactelistices and yield higher output powers and efficiencies.

FABRICATED DEVICE DETAILS

GaAs Gunn devices have been constructed from MBE grown epitaxial structures having $\alpha < 1$ as shown in Fig. 2. The construction details of an IHS fabricated chip are shown in Fig. 3. A standard Au-Ge/Ni/Au ohmic contact was formed on the epitaxial side of the wafer followed by a 30 µm thick gold IHS. The entire semiconductor is thinned to 10-12 µm before defining the mesas. Standard Au-Ge/Ni/Au ohmic contacts were applied to the substrate. The wafers were then diced to form chips having lenghts of 0.008" to 0.010" on each side. Mesa diameters were initially 0.003"-0.004". Individual chips were thermocompression bonded onto the pedestal of a standard picopill (e.g., M/A-COM style ODS-138) package. Contact between substrate and package top surface was made via a gold maltese-cross shaped preform nominally 0.0005" thick. Devices were etched to exhibit a dc threshold current value of 1.0 A and then hermetically sealed within the package with a 0.005" thick (0.030" dia.) gold plated top cap. Devices were also constructed having a doping profile with $\alpha = 1$, cf. Fig. 2. Device fabrication was caried out as described above for devices having $\alpha < 1$.

MEASURED RESULTS

A series of graded active layer profiles having slope parameter $\alpha < 1$ have been grown for operation at Ka and V-band frequencies, cf. Fig. 2. A standard flat profile structure ($\alpha = 1$) has also been grown and evaluated in both heat sink-cathode and heat sink-anode modes. The major results obtained from IHS devices constructed from these materials are given in Table I. In general, both G-111 and G-118 devices exhibited similar performance; however, the reliability of G-118 devices at cold temperatures (-54°C) exceeded that of G-111 devices. This is due, in part, to the lower active layer average doping concentration. The nominal output power of G-111 devices was 285 mW at 31 GHz and 250 mW at 35 GHz, as measured at room temperature in a standard reduced height post-coupled waveguide oscillator. Corresponding efficiencies of 6.5 and 6.25 percent were obtained. When operated in the second harmonic mode in a full height radial disk test oscillator, average power outputs and efficiencies of 50 mW and 1.6 percent were achieved at 67 GHz. Typical operating voltages and currents were -4.8 Vdc, 830 mA and -6.3 Vdc, 520 mA in the fundamental and second harmonic modes, respectively. The difference between ambient turn-on to operating voltage was nominally 0.5 Vdc for both modes.

Devices from G-118 produced nominally 250 mW ($\eta = 6.2\%$) and 225 mW ($\eta = 6.17\%$) at 31 and 35 GHz, respectively, and 40 mW ($\eta = 1.1\%$) at 67 GHz. The turn-on to operating voltage margin was also about 0.5 Vdc.

Flat profile devices from G-44, when operated heat sink positive, nominally produced 200 mW ($\eta = 5.1\%$) and 175 mW ($\eta = 4.8\%$) at 31 and 35 GHz, respectively, and 30 mW ($\eta = 0.75\%$) at 67 GHz. The resulting turn-on to operating voltage margin was only about 0.3 Vdc. Performance with device operation in the heat sink-cathode (i.e., positive substrate) mode was lower: 165 mW ($\eta = 4.7\%$), 135 mW ($\eta = 4.2\%$) and 22 mW ($\eta = 0.6\%$) at 31, 35 and 67 GHz, respectively.

Also shown in Table I is a listing of the best results obtained to date for devices fabricated from each wafer listed on Fig. 2.

Selected devices from wafers G-111 and G-118 (10 each) were tested prior to and after a seven day burn-in, under operating conditions, in second harmonic radial disk circuits. Both dc and rf performance remained essentially constant in all cases.

Measured FM noise at 100 KHz offset from the carrier was nominally -75 dBc/Hz at 67 GHz. Devices were temperature cycled over a -54°C to +85°C temperature range. Devices from G-118 all exhibited well behaved operation over the full temperature range while G-111 devices had normal operation over a-20°c to +85°C range. Some G-111 devices failed at temperatures of -40°C or lower. Device rf performance from G-118 material remained essentially constant after a seven day burn-in and exhibited continuous, well behaved, characteristics over a -54°C to +85°C operating temperature range. Measured FM noise was nominally less than -75 dBc/Hz at 100 KHz offset from the carrier frequency at 67 GHz.

CONCLUSION

Precise control of doping concentration and doping profiles by computer aided MBE permits growth of near ideal GaAs Gunn structures for improved device performance at both fundamental and second harmonic frequencies. By grading the doping profile along the active region to offset the mobility changes caused by self-heating, by operating the device in the heat sink-anode mode ($\alpha < 1$), and by thinning the substrate, enhanced operation of mmW GaAs Gunn devices has been achieved. The efficiencies and power outputs of devices produced from these materials have exceeded those obtained for conventional flat profile devices operated in the heat sink-anode and heat sink-cathode modes. Preliminary results from devices designed to operate near 94 GHz have yielded output powers greater than 50 mW with over one percent efficiency.

Substrate thinning (or complete removal) promises to improve the turn-on characteristics which are marginal in most GaAs mmW Gunn diodes operated in the harmonic mode.

Although comparable performance has been shown for devices having an nn^+ epi-structure (i.e., with the n^{++} contact layer omitted) operating in the heat sink-cathode configuration, only fundamental mode data has been published. Relatively few details and essentially no previous results have been reported for devices having active layer slope parameter $\alpha < 1$ operated in the heat sink-anode configuration in either their fundamental and/or second harmonic modes.

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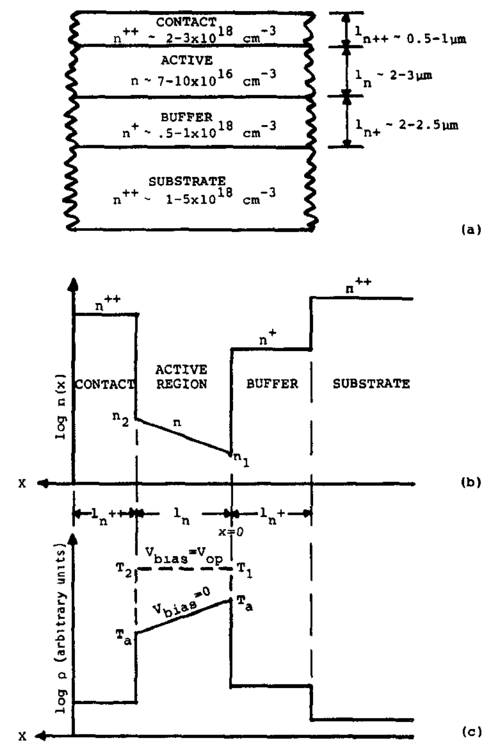
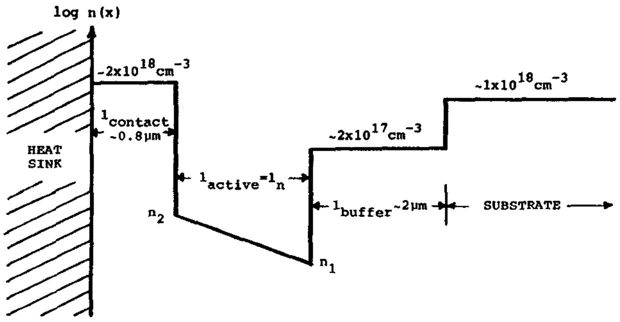


Fig. 1. GaAs bulk effect mmW (a) epitaxial structure; (b) doping profile with slope parameter $\alpha = n_1/n_2$; (c) device resistivity profile showing the effect of self-heating for $\alpha < 1$.



SAMPLE NUMBER	n_1 $(cm)^{-3}$	n_2 $(cm)^{-3}$	l_n (μm)	$\alpha = n_1/n_2$
G-111	$6.7x10^{15}$	$1.3x10^{16}$	2.50	0.5154
G-118	$6.0x10^{15}$	$1.0x10^{16}$	2.62	0.6000
G-44	$9.0x10^{15}$	$9.0x10^{15}$	2.60	1.000

Fig. 2. Fundamental Ka-band (26.5-40 GHz) and second harmonic V-band (50-75 GHz) GaAs Gunn diode doping profile.

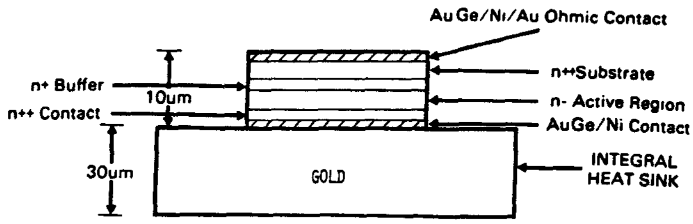


Fig. 3. Integral heat sink (IHS) chip construction details.

DEVICE NUMBER	V_{on} (Volts)	V_{op} (Volts)	I_{op} (mA)	FREQ. (GHz)	POWER (mW)	EFF. (%)	REMARKS
G-111/1/4-3	-4.38	-4.84	906	31.13	285	6.5	typical result
	-4.42	-4.83	828	34.87	250	6.25	" "
	-5.22	-5.80	528	68.05	50	1.6	" "
G-111/1/5-12	-4.60	-5.20	976	31.2	345	6.8	best result
	-4.71	-5.21	967	34.9	325	6.6	" "
	-5.41	-6.33	518	67.8	90	2.75	" "
G-118/4/2-5	-4.65	-5.75	701	31.18	250	6.2	typical result
	-4.80	-5.73	637	34.77	225	6.17	" "
	-6.11	-6.54	556	66.5	40	1.1	" "
G-118/3/5-12	-5.35	-5.80	688	31.10	310	6.4	best result
	-5.42	-5.91	791	67.70	285	6.1	" "
	-6.20	-6.79	511	67.95	88	2.53	" "
G-44/1/3-6	-4.50	-4.70	834	31.3	200	5.1	typical result
	-4.60	-4.72	772	35.2	175	4.8	" "
	-5.30	-5.60	714	66.9	30	0.75	" "
G-44/2/1-4	-4.44	-4.82	920	30.9	235	5.3	best result
	-4.38	-4.78	882	34.8	215	5.1	" "
	-5.45	-5.95	840	67.1	45	0.9	" "
G-44/1/3-6	+4.32	+4.66	753	31.4	165	4.7	typical result
	+4.42	+4.68	687	35.2	135	4.2	" "
	+5.7	+6.0	611	67.0	22	0.6	" "
G-44/2/1-4	+4.26	+4.72	843	31.0	195	4.9	best result
	+4.30	+4.70	724	34.9	160	4.7	" "
	+5.8	+6.2	691	67.0	30	0.7	" "

Table I. Measured dc and rf test results.