Development of an on-wafer test for rapid evaluation of doping spike carrier concentration levels in commercially manufactured GaAs Gunn diodes for automotive radar applications

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ABSTRACT

At e2v Technologies, gallium arsenide Gunn diodes with hot electron injection, based on the heteroepitaxy of a step-graded $Al_xGa_{(1-x)}As$ launcher, are commercially manufactured for 77GHz automotive adaptive cruise control (ACC) systems. Characterization of Gunn diode epitaxial material is problematic, especially the measurement of carrier concentration in the injector's thin (less than 10nm) n^+ doping spike (around $10^{18}cm^{-3}$), which is key for efficient device operation and must be controlled to around ±2.5%. Currently the only methods to verify carrier concentration in this region are (1) growth and characterization of a verification-wafer immediately before the Gunn wafer growth, or (2) statistical analysis of final device characteristics. Neither method is ideal as (1) is accurate to only around ±15%, and (2) requires time-consuming and costly device fabrication before results can be fed back.

This paper discusses the development of on-wafer quasi-planar Gunn diode structures that allow fast, accurate evaluation of spike doping levels using pulsed-DC measurements, without the need for full device fabrication. This test has been successfully demonstrated and is currently being implemented as a wafer release test and as an MBE doping calibration check. Planning is underway to transfer the procedure to an on-wafer, in-process test to be carried out during initial frontside processing, thus leading to a significant reduction in characterization cycle time.

INTRODUCTION

The Gunn diode has long been the favored device for coherent power generation at mm-wave frequencies. Its low phase-noise and moderate output power levels make it ideal for many RADAR and imaging applications. Unfortunately the epitaxial structure of the Gunn diode does not lend itself well to direct characterization using standard techniques. At present injector composition is ascertained from a statistical analysis of fully fabricated device characteristics. In order to verify injector composition *before* device fabrication a new (preferably in-process) method is needed. This would reduce feedback time, avoid expensive device fabrication on out-of-specification-wafers, and reduce the potential for process-induced variations influencing the data.

		Cathode
0.5 *µm*	GaAs *n=5×10^18*	Contact layer
10 *nm*	GaAs undoped	Spacer
50 *nm*	$Al_xGa_{(1-x)}As$	Step-graded launcher
10 *nm*	GaAs undoped	Spacer
<10 *nm*	n^+ GaAs	Doping spike
<2 *µm*	n GaAs	Transit region
0.5 *µm*	n^+ GaAs	Buffer
10 *µm*	GaAs *n=5×10^18*	Substrate
		Anode

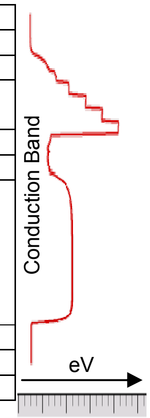

Figure 1. Epitaxial structure and conduction band diagram of a Gunn diode with step-graded $Al_xGa_{(1-x)}As$ hot electron injector (N.B. not to scale).

In the graded-gap injector [1]-[4] structures used here, an n^+ doping spike is necessary to control the electric field at the start of the transit region while retaining the hot electron properties (see Figure 1). In its absence a depletion region is formed behind the launcher in forward bias which inhibits high-field domain nucleation and acts as a 'dead zone' [3], [4]. Several device characteristics are extremely sensitive to doping-spike carrier concentration, including RF output power, applied voltage controlled frequency tuning range (df/dV), and pulse-withstand voltage (V_{pw}). The effects on these parameters of varying spike doping are shown in Table 1, and the effects of an estimated 10% drop in spike doping over four wafer runs, are shown in Figure 2. Analysis of historical data has shown that spike doping needs to be controlled to less than ±2.5% in order to meet the stringent automotive industry specifications for these parameters.

Also listed in Table I is current asymmetry (I_{asym}). This is measured using DC testing and is the ratio of the reverse bias threshold current to the forward bias threshold current. Under forward bias the electric field profile at the start of the transit region, and therefore the maximum current, is determined by the spike, whereas under reverse biasing the electric field profile (and therefore current) is not influenced by the doping spike. This makes I_{asym} a sensitive indicator of spike doping level, which is independent of the composition of other epitaxial regions.

TABLE I
EFFECTS OF SPIKE DOPING VARIATION ON SELECTED FINAL DEVICE CHARACTERISTICS

Material Ref	V1900	V1909	V1901
Growth date	10/21/05	1/16/06	10/26/05
Spike doping	5×10^{17}cm^{-3}	7.5×10^{17}cm^{-3}	1×10^{18}cm^{-3}
Iasym	1.70	1.58	1.22
Pout (mW)	58	70	72
Vpw (V)	16	14.3	9.5
df/dV (MHz/V)	240	600	765

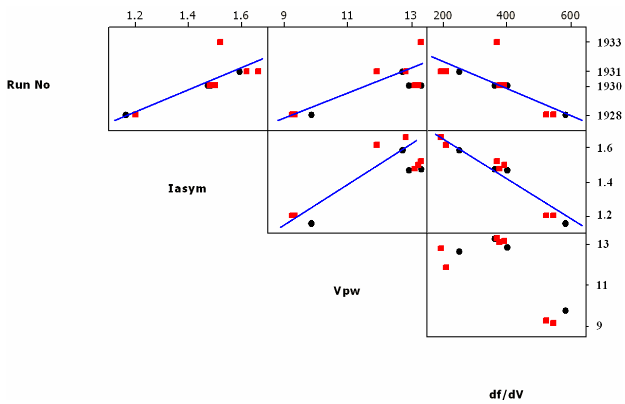

Figure 2. Matrix plot of Run No, I_{asym}, V_{pw}, and df/dV. Red (squares) and black (circles) denote different substrates and the blue lines serve as a guide for the eye only.

Due to the enormous power density (around 130,000 W/cm^2 [4]) in a continuously operating device, determining I_{asym} by conventional DC testing requires that devices are fully processed and include integral gold heatsinks.

ON-WAFER PULSED-DC TESTING OF QUASI-PLANAR GUNN STRUCTURES

An alternative method for obtaining I_{asym} is currently being implemented in the form of on-wafer pulsed-DC testing (which reduces self-heating effects and so the need for heatsinking) of quasi-planar Gunn diode structures (Figure 3). These are quick to fabricate and can be integrated into the initial frontside production process. A wet chemical etch through the epitaxial material to the buffer layer is used to define 70µm diameter mesas. The ohmic contacts consist of a circular cathode contact on the mesa and an annular anode contact to the buffer, formed by patterned deposition (via thermal evaporation) and subsequent alloying of the ohmic contact metal. The ohmic metallization is topped with a thick layer (~200nm) of evaporated gold which allows direct probing of the contacts.

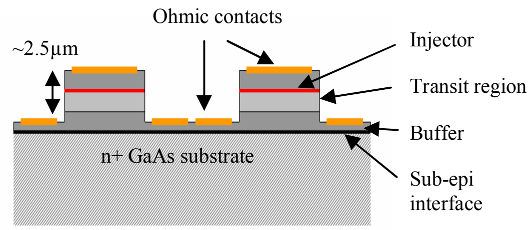

Figure 3. On-wafer quasi-planar Gunn diode structure.

The LabVIEW-based test system consists of a custom built probe head mounted on a micro-manipulator that allows fast, direct probing of the structures. A 100ns pulse, with a rise time of around 5ns, is applied to the structures at a frequency of 1KHz and the I-V characteristics are extracted from a 100MHz dual-trace oscilloscope as the pulse voltage is varied.

RESULTS AND DISCUSSION

A typical set of traces can be seen in Figure 4. Note that true negative differential resistance is not seen, due to the lack of self-heating in the device.

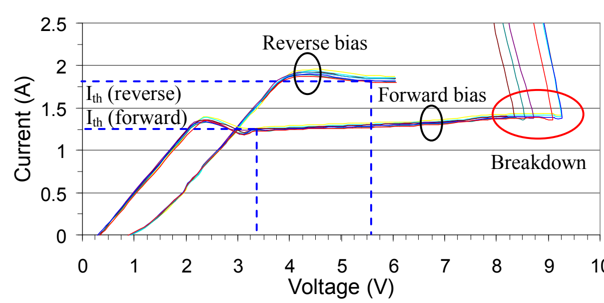

Figure 4. Typical pulsed-DC I-V plots for 8 on-wafer structures.

The 'hump' which can be seen just above the knee of both the forward and reverse bias pulsed-DC I-V plots (more pronounced in the forward case) is due to the transient-response evolution of the pulses as the voltage is increased and can be disregarded here. The threshold current (I_{th}) values used to calculate asymmetry are taken just after the knee as indicated in Figure 4.

The pulsed-DC I_{asym} values are higher than those obtained using constant DC measurements due to the different degree of self-heating. However, there is strong correlation between asymmetry values obtained from DC testing of fully fabricated and packaged devices and those obtained from pulsed-DC testing of on-wafer quasi-planar structures. This can be seen in Table II and Figure 5.

TABLE II
COMPARISON OF CURRENT ASYMMETRY VALUES OBTAINED VIA PULSED-DC AND SWEPT-DC TESTING

Material*	X55	X76	X113	V1937	V1938
Growth date	2/3/06	7/13/06	3/13/07	9/12/07	9/12/07
Growth campaign	1	2	2	-	-
Swept-DC	1.59	1.33	1.18	1.10	1.08
Pulsed-DC	2.1	1.73	1.57	1.53	1.53
(* Letter denotes MBE reactor used: X=V100+, V=V90H)					

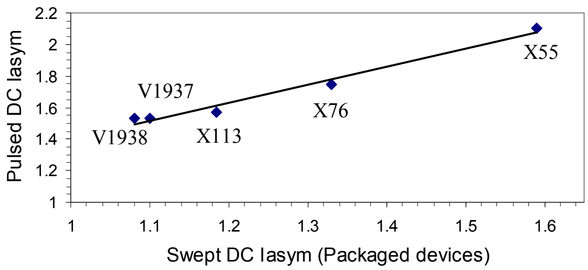

Figure 5. Swept-DC current asymmetry (of packaged devices) vs. pulsed-DC current asymmetry of on-wafer devices.

The variation in I_{asym} values (and therefore spike doping level) for the material in Figure 5 and Table II can be attributed to a number of causes. Firstly material grown in two different Oxford Instruments MBE reactors is presented: X denotes growth in a V100+ (a multi 4" wafer reactor), while V denotes growth in a V90H (single 4" reactor). The difference between X55 and X76 is due to a combination of a deliberate 10% increase in spike doping level (which corresponds to a 2.5ºC increase in the nominally 1080ºC Si dopant cell temperature) and a suspected process drift over time. X113 was grown during the early stages of a new growth campaign (i.e. shortly after the reactor was opened to atmosphere to replace sources and to perform maintenance operations).

An additional point of interest is the small difference in the swept-DC I_{asym} values between V1937 and V1938. These were grown on the same day to the same specification meaning any drift in doping spike carrier concentrations should have been minimal. The pulsed-DC I_{asym} values are equal which suggests identical spike doping levels and, in turn, the possibility that process induced variation has affected the swept-DC values taken from fully fabricated and packaged devices.

Another device parameter that can be estimated from the pulsed I-V data is the pulse-withstand voltage (defined as the pulse voltage at which a device breaks down). This forms the basis of a reliability test designed to eliminate diodes that are susceptible to damage by static discharge or bias circuit oscillations. Table III shows the correlation between V_{pw} values obtained in package and on-wafer. The small differences between the two sets of values is again thought to be due to process induced variation. Although the correlation between the two sets of data is not as strong as that for I_{asym}, a good indication of whether V_{pw} will be above a specified value can be obtained.

TABLE III
COMPARISON OF PULSE-WITHSTAND VOLTAGES OBTAINED FROM IN PACKAGE AND ON-WAFER TESTING

Material	X55	X76	X113	V1937	V1938
In package	12.16	11.5	11.4	9.5	9.1
On-wafer	10.25	13.0	11.6	9.8	9.0

CONCLUSIONS

Pulsed-DC testing of on-wafer quasi-planar Gunn diode structures has been shown to allow fast feedback of information relating to the carrier concentration in the hot electron injector n^+ spike. This has the potential to become an extremely powerful statistical tool as more data is accumulated. An additional benefit is an estimation of the final device's pulse-withstand voltage. This technique has been incorporated into the standard material characterization procedure for Gunn wafers as a release test. It is also planned to include it in e2v's in-process production line testing.

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ACRONYMS

ACC: Adaptive Cruise Control
DC: Direct Current
RF: Radio Frequency
MBE: Molecular Beam Epitaxy