Fabrication and Characterisation of GaAs Gunn Diode Chips for Applications at 77 GHz in Automotive Industry

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Abstract: GaAs-based Gunn diodes with graded AlGaAs hot electron injector heterostructures have been developed under the special needs in automotive applications. The fabrication of the Gunn diode chips was based on total substrate removal and processing of integrated Au heat sinks. Especially, the thermal and RF behavior of the diodes have been analyzed by DC, impedance and S-parameter measurements. The electrical investigations have revealed the functionality of the hot electron injector. An optimized layer structure could fulfill the requirements in adaptive cruise control (ACC) systems at 77 GHz with typical output power between 50 and 90 mW.

Keywords: Gunn diode, microwave generation, GaAs hot electron injector.

Introduction

Automotive electronic systems are permanently increasing in complexity and they are meanwhile integrated in the whole electronic car management. A quite new sensor system is the Adaptive Cruise Control System (ACC) from Robert Bosch Company. The system is based on a microwave generator, which enables the detection of the position and the velocity of cars driving ahead. Depending on their velocity, the system will accelerate or slow down the driver's car if necessary. In this sense, the modern car has an intelligent electronic co-driver, which is permanently watching the traffic situation and engages in the car-management if this requires it.

The actual ACC system from Robert Bosch Company is based on a GaAs Gunn diode microwave oscillator. The Gunn diode is therefore the key-element for the performance of the system.

GaAs-based Gunn diodes are quite old devices. J.B. Gunn discovered in 1963-64 [1,2] that in III/V materials, like GaAs or InP, in addition to the DC current, a superimposed microwave signal of high frequency appeared if the applied bias field exceeded a certain threshold value. The microwave frequency is proportional to the electron drift velocity and the sample length. The origin of this effect has been found in the band structure of the studied semiconductors: at high electrical fields electrons will be scattered from the Γ- to the L-valley. L-valley electrons have less mobility than Γ-electrons, so that electron drift velocity as a function of the electrical field presents a region of negative differential mobility (NDM). A charge-fluctuation results in an electrical domain formation if the applied electric field is situated in the NDM region. The space-charge nonuniformity grows exponentially and becomes stable, propagating with the electron drift velocity outside the domain. A new domain can only be generated when the propagating domain reaches the end of the sample. As a result a stable frequency output appears.

In the late eighties, a graded AlGaAs layer placed in front of the active region has improved significantly the performances of the classical Gunn diode [3-5]. Such a graded barrier, in combination with a thin highly doped layer, acts as a 'hot electron injector', increasing the intervalley electron transfer and reducing the dead zone from the beginning of the device active region. As a result, the graded gap injector Gunn diode has superior noise performance, temperature stability and power conversion efficiency. Epitaxial growth methods as molecular beam epitaxy (MBE) permit an accurate control of the AlGaAs grading and the doping of the active region.

In this contribution, the development and optimisation of a graded gap hot electron injector Gunn diode is presented. It is shown that additional spacer layers adjacent to the graded gap region avoid dopant segregation and preserve the role of the electron injector.

The fabrication process of the Gunn diodes is based on a new approach, the complete substrate removal using an AlGaAs layer. The mechanical stabilization of the Gunn diode structure, realized from plated Ni, makes possible the precise plasma mesa etching for the device definition. Compared with the conventional way in which the substrate is not totally removed, this fabrication technology has increased the homogeneity, the reproducibility and the reliability of the diodes.

Finally, S-parameter and impedance measurements carried out on specific planar processed devices constitute a novelty in the characterisation of the graded gap injector Gunn diodes, giving a better understanding of their RF and temperature behaviour.

Experimental

Layer structure

The Gunn diode layer structure (see Table 1) has been grown by MBE on a 2", 200 µm thick, semi-insulating GaAs substrate, in a Varian ModGenII machine. This is based on structures suggested by Hutchinson et al.[3] and Couch et al. [4] and then optimised by Stock [6]. In principle, it consists of an undoped AlGaAs graded barrier structure followed by a δ-doping and a thick low doped GaAs active region. The grading is linear, starting from 1.7% up to 30% Al concentration. An innovative insertion of two 5 nm GaAs spacers avoid doping segregation in the graded barrier. The layer structure has been designed for high power and efficient microwave generation.

Table 1. Gunn diode layer structure.

500 nm	GaAs	$n=5E18cm^{-3}$	contact layer
10 nm	GaAs	-	spacer layer
50 nm	GaAs $\rightarrow$ Al$_x$Ga$_{1-x}$As	-	AlGaAs injector
10 nm	GaAs	-	spacer layer
5 nm	GaAs	$n=1E18cm^{-3}$	delta doping
1.6 µm	GaAs	$n=1E16cm^{-3}$	Gunn drift zone
500 nm	GaAs	$n=5E18cm^{-3}$	contact layer
500 nm	Al$_{0.6}$Ga$_{0.4}$As	-	etch stop layer
50 nm	GaAs	-	buffer
Substrate			

Gunn diode chip processing

GaAs Gunn diode chips operate usually at a DC current of 1 A and a supply voltage of 5 V. The corresponding power density is around 130 000 W/cm^2 leading to an enormous heating of the devices. Therefore, the heat transfer is essential for the diode operation and must be as efficient as possible. Finite element calculations have shown that the Gunn diode placed on top of a GaAs substrate heats up to 915 K. However, when the Gunn diode is in direct contact with an Au heat-sink, on top of a copper block, the steady-state operating temperature decreases to 475 K [7,8]. Therefore, the developed fabrication process is based on the complete substrate removal by selective etching down to the Gunn diode layer structure, in combination with the realization of an integrated Au heat sink and a thick Au plated top contact. In the following, main aspects of the processing are described. Immediately after the epitaxial growth of the heterostructure, the ohmic contact is evaporated on the whole wafer. The contact metallization consists of 20 nm Ge, 15 nm Ni and finally, 200 nm Au. Afterwards, this is annealed at 400 °C for 75 s in N$_2$ atmosphere, obtaining a typical specific contact resistance of

$\rho_C \approx 7 \cdot 10^{-7} \Omega cm^2$. 350 µm round heat-sinks are defined with SU-8 resist direct on top of the ohmic contact. This serves as an electrode for the next step, the plating of a 40 µm thick Au layer (Figs.1, 2).

The next steps are carried out on 1 x 1 cm^2 samples. Before the substrate removal, which leaves only the residual 3 µm Gunn diode heterostructure, the sample has to be first stabilized. This operation is realized by plating a 40 µm thick Ni layer on the sample side with heat-sinks. The Ni layer is very hard and stabilizes the sample perfectly for further process steps.
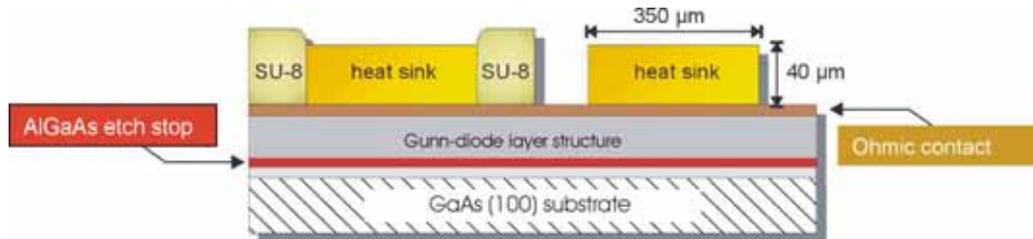
Figure 1. Principle sketch of the first processing steps: heat-sink definition and gold plating.
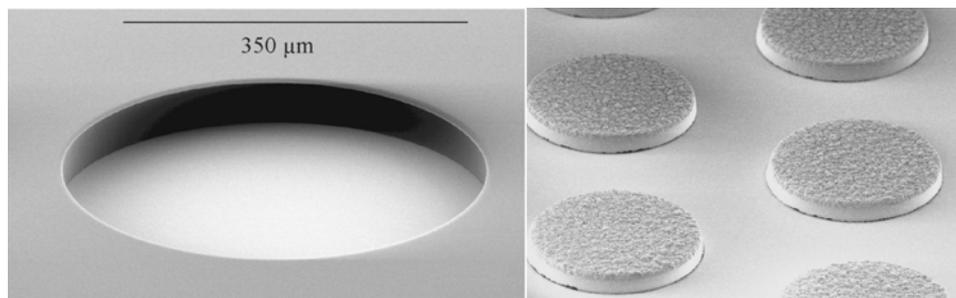

Figure 2. Heat-sink definition with SU-8 resist (left), plated heat-sinks (right).

The 200 µm thick GaAs substrate is then removed in two steps: the first 150 µm are fast etched in a sulfuric acid based solution (H$_2$SO$_4$:H$_2$O$_2$:H$_2$O = 1:8:40; r = 1 µm/min), while the last 50 µm are removed using selective etching of GaAs/AlGaAs in a citric acid based solution (C$_6$H$_8$O$_7$:H$_2$O$_2$ = 4:1; r = 0.43 µm/min) [9]. Finally, the Al$_{0.6}$Ga$_{0.4}$As etch stop layer is rapidly etched in a diluted hydrofluoric acid solution (HF:H$_2$O = 1:1)[10].
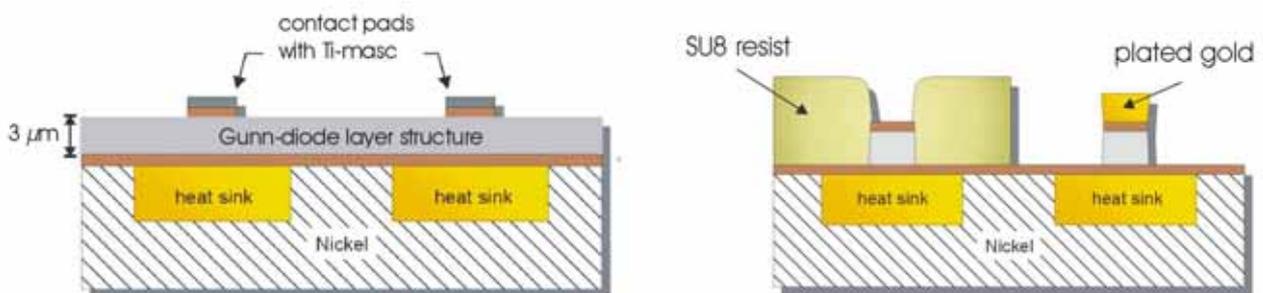

Figure 3. Sketch of the top contact definition, mesa ECR-RIE and top Au plating.

The processing continues with the top contact deposition (Fig. 3). The metallization is similar with that of the bottom contact except an additional Ti layer. This layer serves as a mask for the mesa definition using an ECR (Electron Cyclotron Resonance) reactive ion etch (RIE) process with a Cl$_2$-H$_2$-Ar gas mixture [11]. Then, the top contact pads are reinforced with an additional 5 µm plated gold

layer. In the last step, the Ni stabilization layer is removed (with 5 g FeCl$_3$:100 ml Ethanol: 2 ml HCl) and single Gunn diode chips are separated (Fig 4).
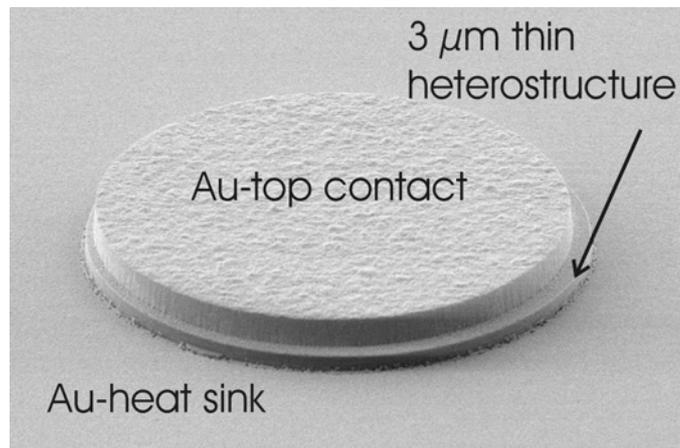

Figure 4. Gunn diode chip: 3µm Gunn-diode heterostructure between two thick Au contacts.

Gunn diode chip packaging and mounting in an oscillator

After processing, the Gunn diode chip is dye-bonded on top of the Cu block of the package and isolated with a ceramic ring. The top contact is wired with a gold Maltese cross and the package is covered with a Au-plate. Finally, the package is built inside an oscillator. The principle sketch of the complete mounting operation is shown in Fig. 5.
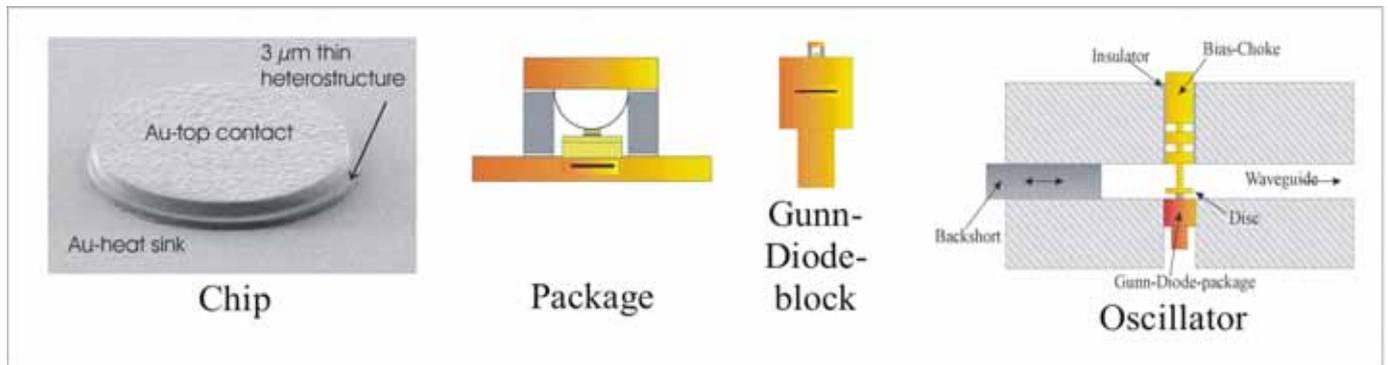

Figure 5. Sketch of the packaging and mounting to the oscillator: chip → package → Gunn-diode block → oscillator.

Planar Gunn diode chip processing

For S-parameter measurements a planar layout with air bridge interconnection is used. We have established that suitable processed planar Gunn diodes can work even laying on top of a GaAs substrate. The absolute power is reduced because of the mesa size of typically 20 x 20 µm^2. Furthermore, the heat is efficiently transferred via a top Au-plating layer.
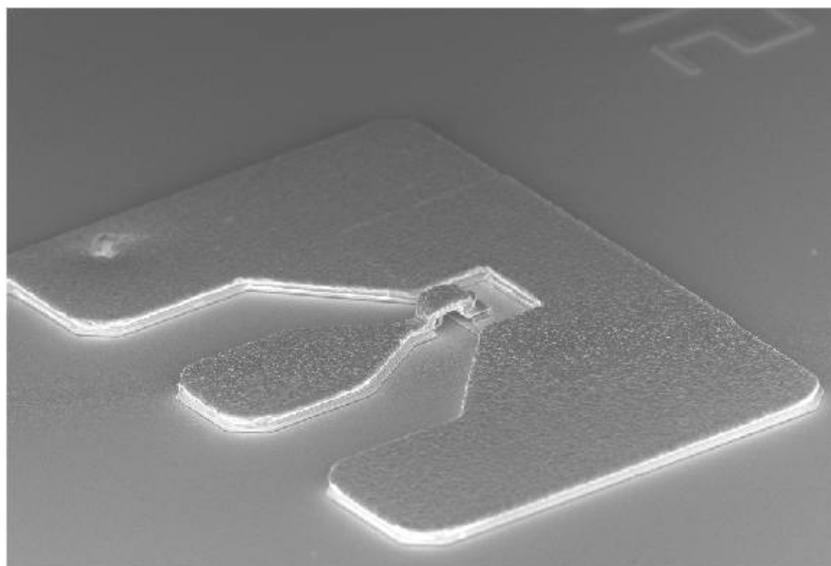
Figure 6. Coplanar layout for S-parameter measurements with air bridge interconnection.

Some of the process steps described above for the fabrication of the normal Gunn diode are used to fabricate the planar Gunn diode as well. First, 2.3 µm deep mesas are processed: 450 nm Ti is evaporated and used as a mask for ECR-RIE. Ge/Ni/Au (20/15/200 nm) self-aligned emitter and collector contacts are deposited and alloyed at 400 °C for 75 s. The devices are electrically isolated with a 600 nm wet chemical etching down to the semi-isolating GaAs substrate. After coplanar waveguide pad deposition, the top contact (emitter) is connected via air-bridges to the middle pad (see Fig. 6).

Results and discussion

DC and impedance measurements, the heat distribution

In Fig. 7, the band structure of the graded gap injector Gunn diode is shown, with and without supply voltage. For a certain bias voltage, electrons are injected from the left side direct into the active zone of the Gunn-Diode with an overshooting energy ΔE equal to the Γ-L band offset. In this case, the electrons are "hot electrons" and can directly be scattered into the L-valley. In conventional Gunn diodes, without hot electron injection, the electrons have to be first accelerated up to the Γ-L band offset energy ΔE. This results in the formation of a dead zone at the beginning of the active region, in which no electrical domain formation appears. It has been estimated that this length is of the order of 0.25 µm. In the case of a graded gap Gunn diode this dead zone is drastically reduced to about 30 nm [4,5].

Typical I-V curves of a graded gap Gunn diode are shown in Fig. 8, for the forward and the backward current direction and continuous and pulsed mode. As a result of heating effects, the I-V curve shows a negative differential resistance region after the threshold only in the continuous mode. In the pulsed mode with 100 ns current pulses, the I-V curve follows the theoretical prediction, having a slightly current increase after the threshold voltage. In the forward direction, electrons are injected into the Gunn diode active region via the graded gap emitter. However, in the backward direction, this

is behind the active region and therefore, not active. Instead of a hot electron injector, it acts in this case only as a series resistor. Therefore, one can say that both normal and graded gap injector Gunn diodes are encountered in one device. The strong difference between the peak current in the backward and the forward directions, especially in the pulse mode, is related to the different electron drift velocities in these directions and thus, it is a measure of the L(Γ)-valley occupation. In the forward direction, one assumes an electron injection directly into the L-valley where they have a lower drift velocity, leading to a lower peak current. In contrast to this, the L-valley occupation is much lower in the backward direction and consequently, the peak current is much higher (higher Γ-valley occupation).
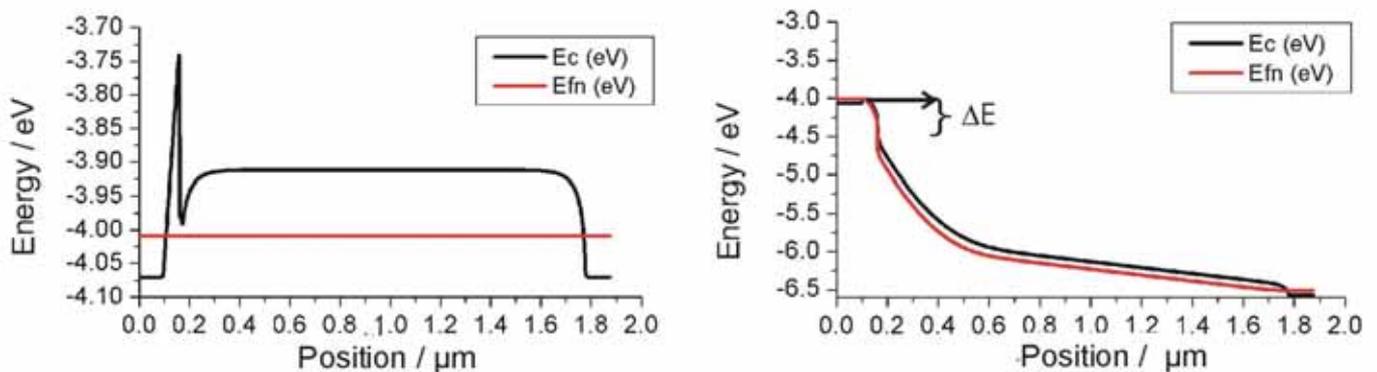

Figure 7. Band structure across the Gunn diode according to Table 1: without supply voltage (left) and with supply voltage (right).
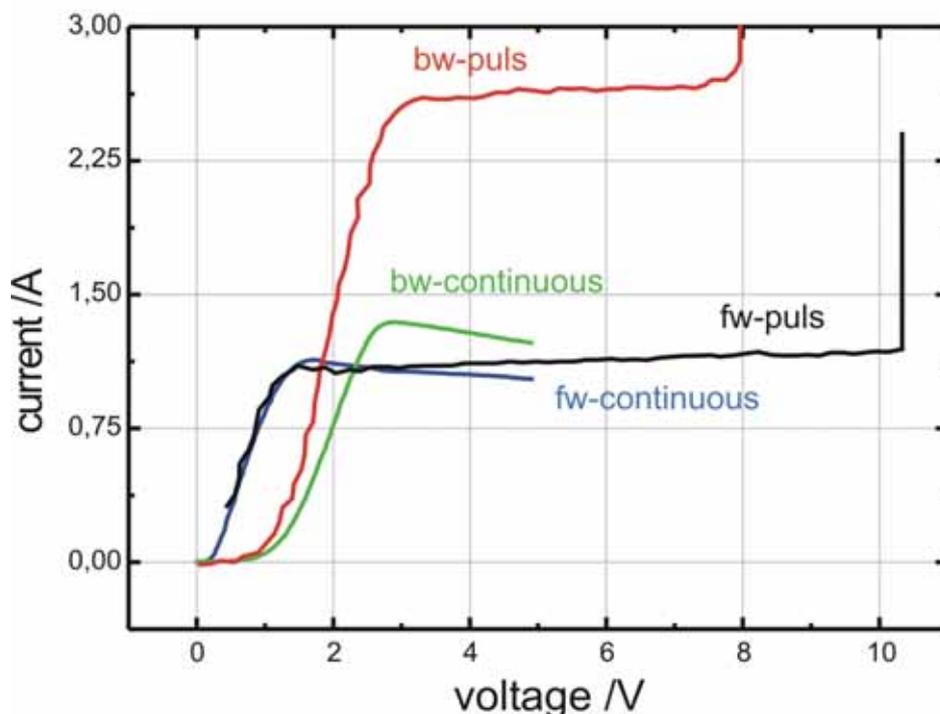

Figure 8. Graded gap Gunn diode I-V curve, "bw-puls" and "fw-puls" denotes the backward- (bw) and forward- (fw) directions measured in the 100 ns pulse mode, "bw-continuous" and "fw-continuous" denotes the backward- and forward- directions measured in the continuous mode.

It is obvious from the measurements (Fig. 8) that in the backward direction, there is a large difference between the peak current in the pulsed mode and that one in the continuous mode. This can be correlated with the extreme heating of the narrow reverse biased injector. Most of the total voltage will drop on the injector in this case, whereas in the forward direction, the voltage drop is much more homogeneous and the injector appears not as a relevant series resistor. In addition, the total power in the backward direction is higher than in the forward direction. In conclusion, the combined continuous and pulsed DC measurements demonstrate the role of the graded gap injector concerning both the efficiency of the electron transfer in the L-valley and minimisation of the heating effects.

Impedance measurements on planar Gunn diodes can give important information about the transition from negative differential resistance to positive one in the I-V characteristics and about the heat distribution inside the device. In Fig. 9, the real part of the measured impedance is presented as a function of the frequency for a Gunn diode without spacer layers (see Table 1). Because of Si segregation from the adjacent high doped layers, the barrier effectiveness is destroyed and the diode behaves like one without graded gap injector. As a result, the I-V characteristics is nearly symmetric with respect to the forward and the backward directions [6]. The impedance measurements for such a Gunn diode (Fig. 9) show that the transition frequency from negative to positive differential resistance is almost independent of bias voltage, being situated between 100 and 200 kHz. This behaviour can be understood considering a homogeneous heat distribution across the sample. As a consequence, the total diode mass is heated and the temperature changes can be described using a thermal RC circuit [6].

Within this model, the thermal resistance can be written as $R_{th} = \dfrac{d}{\lambda A}$, were d is the length of the sample, λ is the thermal conductivity and A the area of the sample, and the thermal capacity as $C_{th} = c_v m = c_v A d \rho$ where m is the diode mass, ρ is the density, and c_v the specific heat capacity. The thermal RC circuit has a typical time constant $\tau = C_{th} R_{th} = \dfrac{c_v \rho d^2}{\lambda}$ and the corresponding thermal transition frequency is $f = \dfrac{\lambda}{c_v \rho d^2}$. For a 3 µm thick GaAs mesa (c_v=350 J/(Kkg), λ=54 W/(Km), ρ=5.5 g/cm^3) the transition frequency is 3.1 MHz. A comparison between this value and the experimental one situated between 100 and 200 kHz leads to the assumption that the GaAs mass below the diode is also significantly heated. In this sense, if one considers a 10 µm thickness of GaAs material, the calculated transition frequency is 281 kHz, which is closed to the experimental result.

A Gunn diode with hot electron injector (spacer layers) does not follow anymore the model described above [8]. As seen in Fig. 10, the transition frequency is not anymore constant but shifts to lower values with higher supply voltages. This demonstrates an inhomogeneous heat distribution across the active layer. At low voltages, mainly the injector side is heated, whereas at higher voltages, the total active layer is heated homogeneously (at 4 V the transition frequency is between 100 and 200 kHz, like for diodes without injector).
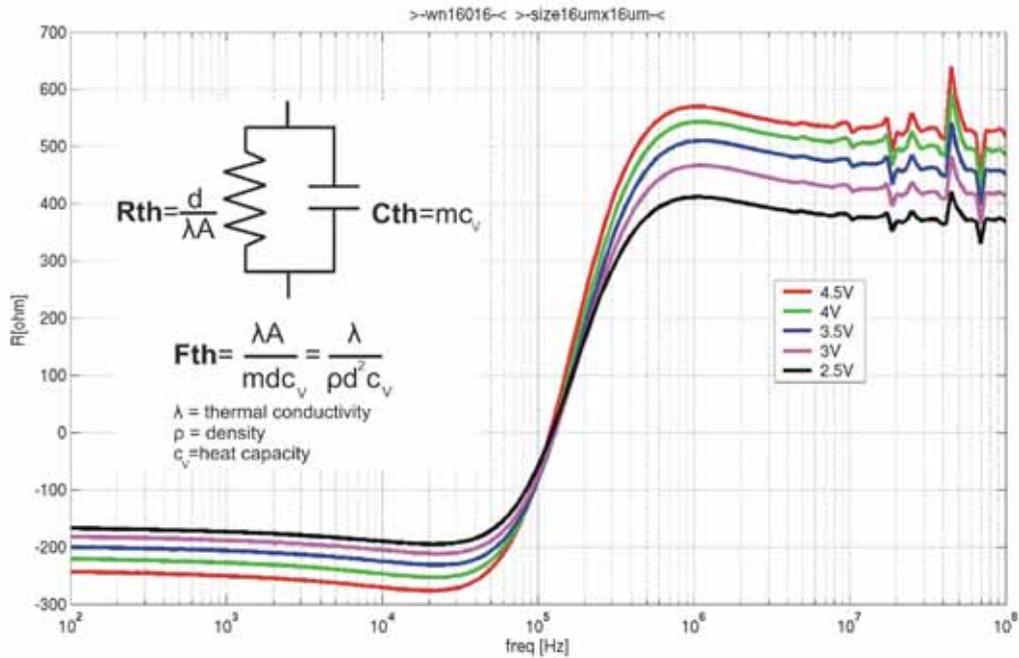
Figure 9. Impedance measurements of a Gunn diode without spacer layers at different supply voltages.
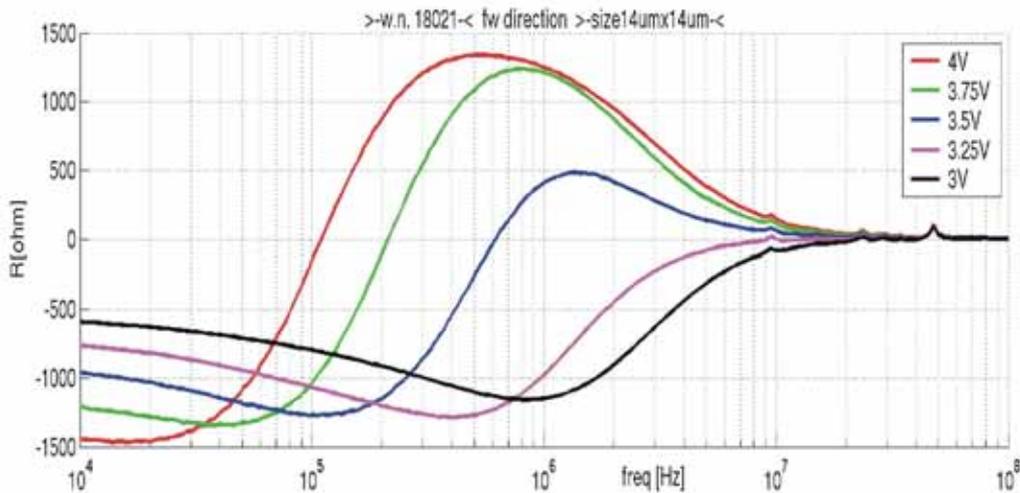

Figure 10. Impedance measurements of a Gunn diode with spacer layers at different supply voltages.

High frequency results

Our Gunn diodes fabricated for ACC system applications achieved an output power between 50 and 90 mW, at the second harmonic frequency of 77 GHz. The diodes fulfilled the internal BOSCH specifications with respect to the frequency stability, the electrical tuning range and the power output, which represent the basis for an ACC application in automotive industry. In this sense, this development could be assigned as a feasibility study for starting a production line.

In the case of a complete Gunn diode oscillator, it is hard to distinguish between Gunn diode effects and oscillator effects at high frequencies. From this point of view, it would be helpful to get pure Gunn diode related high frequency results before packaging and building up the oscillator. S-parameter measurements up to 110 GHz are suitable to measure the distinct behaviour of the hot electron injector.

In this sense, the drift velocity and the occupation of Γ- and L-valleys can easily be extracted from such measurements [12].

The graded gap hot electron emitter should lead to the domain formation at the very beginning of the Gunn diode active zone and hence, to a narrow frequency band. This behaviour can also be demonstrated using S-parameter measurements. In one port measurement configuration, the input reflection coefficient |S11| describes the ratio of the outgoing to the incoming power. The direct comparison between the results for the diode without and with hot electron injector is shown in Fig. 11 [8]. One clearly sees the main effect of the injector. Whereas the diode without hot electron injector exhibits in the measurements a broad |S11| resonance band, the hot electron emitter diode shows a very sharp resonance peak with a high |S11| value. This clearly demonstrates the functionality of the hot electron injector.
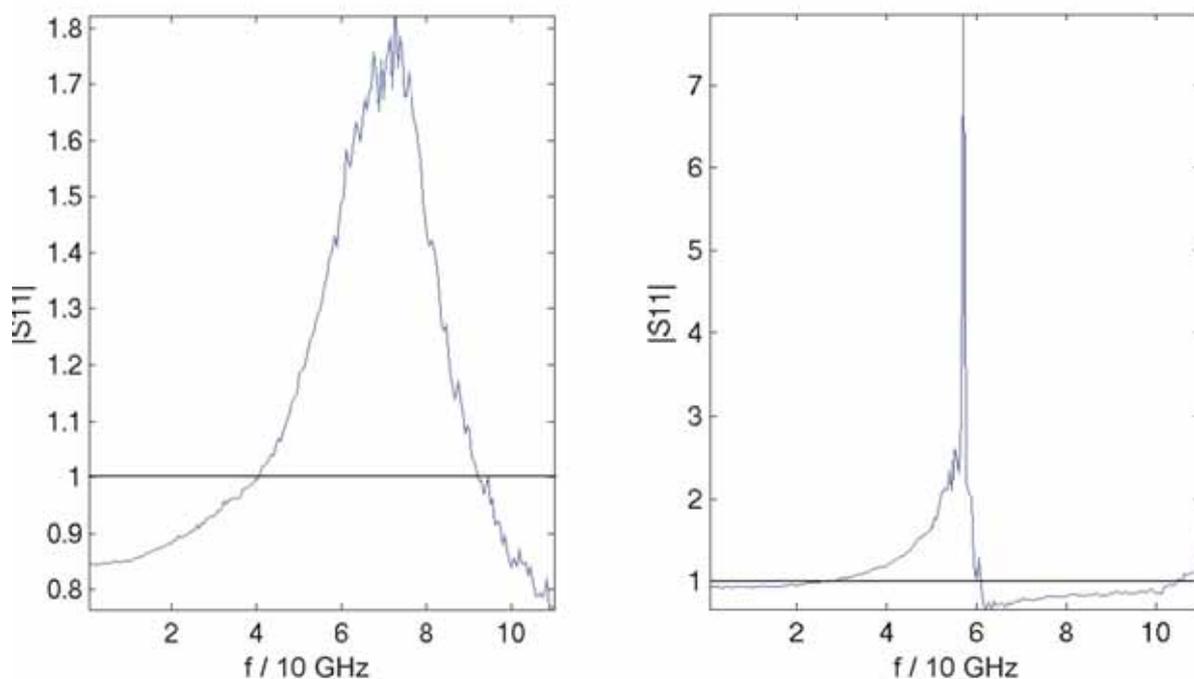

Figure 11. One port S-parameter measurements of the Gunn diode up to 110 GHz: without hot electron injector (left), and with hot electron injector (right).

Conclusions

We have presented the layer structure and detailed process steps for the fabrication of graded gap injector Gunn-Diodes that fulfil the specifications in automotive industry. Pulse and continuous DC measurements demonstrate the role of the graded gap injector concerning both the efficiency of the electron transfer in the L-valley and minimisation of the heating effects. Information about the heat distribution inside the Gunn diode, without and with effective injector, and conditions for transition from negative differential resistance to positive one in the I-V characteristics are extracted from impedance measurements. High frequency results obtained by S-parameter measurements show a narrow frequency band reflecting the functionality of the hot electron injector.

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