Monolithically Integrated GaInP/GaAs High-Voltage HBTs and Fast Power Schottky Diodes for Switch-Mode Amplifiers

P. Kurpas, A. Wentzel, B. Janke, C. Meliani, W. Heinrich, J. Würfl

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), Gustav-Kirchhoff -Str. 4, 12489 Berlin, Germany
Phone: +49-30-6392-2674, fax: +49-30-6392-2685, e-mail: paul.kurpas@fbh-berlin.de

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Abstract

Based on mature and high-yield high-voltage (HV) HBT technology monolithically integrated ultra-fast Schottky diodes are developed. The Schottky diodes take full advantage of the optimized HV-HBT layer structure allowing for diode´s breakdown voltage of 80 V. Due to optimized thermal mounting using priopriatery flip-chip soldering high current switching capability up to 4 A at 60 V was demonstrated. On the other hand, short diode´s recovery time of 9 - 12 ps was evaluated. Thus, the integrated HV-HBTs and Schottky diodes are well suited for high speed MMICs for power applications. Novel switched-mode power amplifier circuits were fabricated yielding a digital output power of 5.4 W with very high collector efficiency of 92% at data rates of 1.8 Gbps.

INTRODUCTION

GaInP/GaAs heterojunction bipolar transistors (HBTs) are available for microwave power applications not only in the low-voltage region as commonly used in mobile handsets but also at higher operation voltages up to 36 V delivering 10+ W of output power at 2 GHz [1]. Due to its high efficiency and high linearity [2] such high-voltage HBTs (HV-HBTs) are well suited for power amplifiers (PAs) as required e.g. for applications in cell-phone base stations. Recently, efficiency record of PAE ~ 58% for a single-stage wideband HV-HBT-based PA was reported [3].

In this paper, we report on successful monolithic integration of such 'high-voltage' HBT power cells with ultra-fast high-voltage blocking Schottky diodes as required for next generation switch-mode power amplifiers.

The challenge in realizing such diodes is to combine 70 V blocking voltage with high forward current (2…3 A) and an ultra-low time constant. The basic idea was to use a Schottky diode formed by a metal contact on the collector part of the HBT layer structure for this purpose. The lowly n-doped (~$5x10^{15}$ cm^{-3}) and 3 µm thick collector layer ensures the high breakdown voltage. Since the Schottky diode should be capable of handling high currents up to 3 A, proper heat sinking is important for this device, too. Hence, we adapted here the thermal concept of the HV-HBTs including FBH´s proprietary flip-chip soldering technology [4].

EXPERIMENTAL

The high-voltage HBT structures (HV-HBTs) are grown in-house on 100 mm GaAs substrates in a MOVPE reactor. The layer structures mainly consist of a 700 nm GaAs subcollector layer (n=$5x10^{18}cm^{-3}$), an up to 3500 nm thick GaAs collector layer (lowly doped in a region of 4 - $6x10^{15}$ cm^{-3}), a 100 nm GaAs base layer (p=$4x10^{19}$ cm^{-3}), a 40 nm $Ga_{0.51}In_{0.49}P$ emitter layer (n=$5x10^{17}$ cm^{-3}), and GaAs and InGaAs contact layers. Si and C are used for the n-type and p-type doping, respectively. Higher resistance layers are included in the HBT structure as emitter ballast in order to increase the electrical and thermal stability of the device.

The HBT process technology is based on a two-mesa approach in order to access the base and the collector layers. Due to the very thick collector layer the mesa formation is based on a combined dry- and wet-etching approach. For device isolation He-ion implantation of the highly doped sub-collector layer is used. For a full MMIC processing MIM-capacitors with SiN_x dielectric layer and NiCr thin film resistors are included. Interconnections are made by Ti/Pt/Au metal and 3.5 µm thick electroplated Au air bridges. For power cells emitter thermal shunts are formed by a 20 µm thick electroplated Au layer.

Since during HV-HBT front-end processing emitter and base layers are etched as required for the mesa-type HBT device the collector layer is directly accessible. Thus, Schottky diodes can be fabricated by evaporating the Schottky-metal on the thick collector layer as grown for the

HBTs. The n-contact of the diode is made by the same metallization as used for the collector contact for the HBTs. Thus, easy integration of both device types can be performed. The devices are then thermally shunted by thick Au plating, which is used also for flip-chip mounting. Fig. 1 shows integrated HV-HBTs and Schottky diodes as a part of an amplifier circuit.

$WSiN_x$ as the Schottky metal was chosen due to its sufficiently high barrier height and its thermal stability combined with its suitability for operation at high current densities.

Semiconductor surface conditioning prior to Schottky metal deposition is of crucial importance for the diode properties. Therefore, careful process optimization has been performed including the comparison of wet and/or dry-etching for surface preparation. The successful process optimization translates into good ideality factors as obtained for the Schottky diodes given in Table 1. Furthermore, high process stability and high yield is verified by the low standard deviation values obtained from mappings of 70 single devices on a 100mm-wafer.

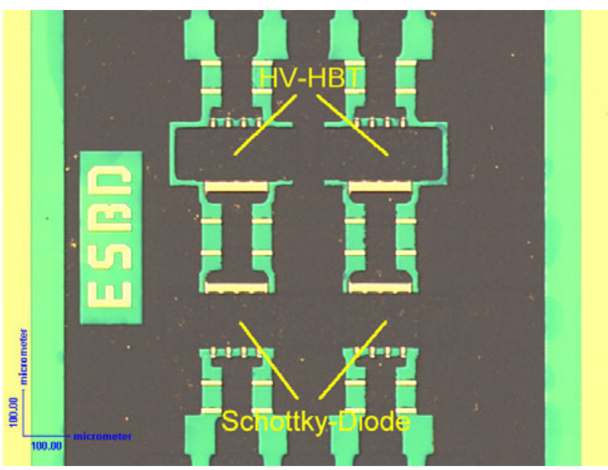

Fig. 1 Viewgraph of integrated HV-HBTs and Schottky diodes prepared for flip-chip mounting.

SCHOTTKY DIODE CHARACTERIZATION

Firstly, the power performance of the Schottky diodes was evaluated by DC-measurements. Fig. 2 shows the forward characteristics of the largest of the fabricated Schottky diodes underlining its current handling capability at high currents up to 2.7 A. Table 1 gives the forward currents at a forward voltage of 2 V for 3 types of Schottky diodes with different active areas. Already the smallest diode with 10 diode fingers in parallel handles currents higher than 1 A.

Fig. 3 confirms that the Schottky diode fully utilizes the potential of the HBT´s collector layer with breakdown voltages higher than 70 V. Such high breakdown voltages were obtained regardless of the size of the Schottky diode (Table 1). These values correspond to the base-collector breakdown voltage of the HV-HBTs [4].

Detailed evaluation of power switching capability of the Schottky diodes was performed on packaged single diodes at Technical University Berlin. The 20-finger Schottky diodes are able to switch currents as high as 4 A at operating voltage of 60 V. Furthermore, superior performance in terms of lower recovery current and shorter recovery time in comparison with a commercially available 100V-class Schottky diode (MBRS3100T3) was observed [5].

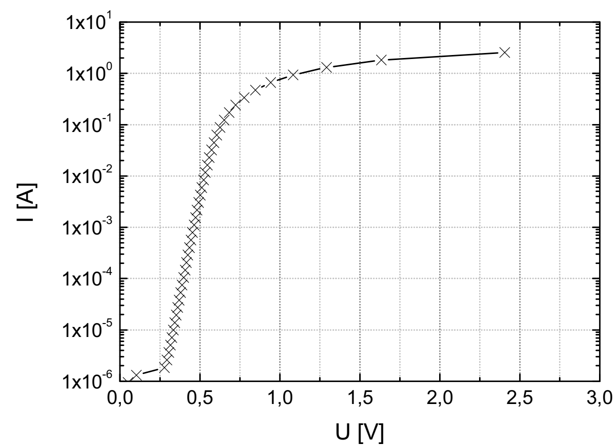

Fig. 2: Forward characteristic of a 20-finger power Schottky diode showing its high-current driving capability.

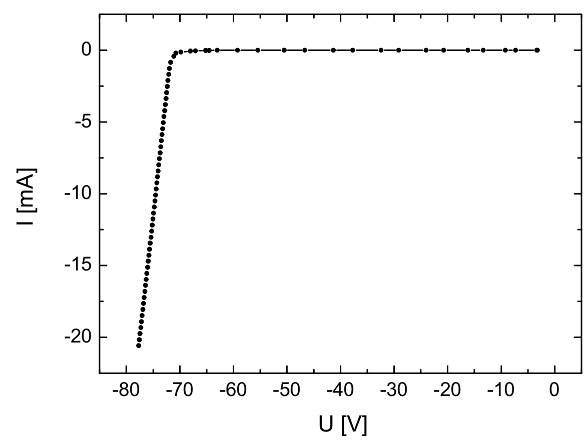

Fig. 3: Reverse characteristic of a 20-finger power Schottky diode showing its high-current blocking capability at voltages higher than 70 V.

TABLE I
CHARACTERIZATION RESULTS FOR FLIP-CHIP MOUNTED POWER SCHOTTKY DIODES IN DEPENDENCE ON THEIR ACTIVE AREA

	Schottky diode type		
	TH-D-10	TH-D-16	TH-D-20
number of fingers	10	16	20
Submount for flip-chip mounting	AlN	AlN	AlN
active area [μm^2]	9360	14976	18720
ideality	1.101	1.097	1.096
ideality std. dev.	0.006	0.005	0.004
barrier height [eV]	0.737	0.736	0.737
barrier height std.dev. [eV]	0.013	0.007	0.007
forward current @2V [A]	1.3	1.8	2.3
breakdown voltage @20mA [V]	80	78	78
measured recovery time [ps]	290	450	590
extracted recovery time [ps]	9	10.6	12.1

The recovery time of a diode is of special importance for switching microwave applications. Thus, special time-domain measurements were performed in order to obtain the genuine values.

In figures 4 the time-domain measurements are presented which compare the switching behavior of a 20 finger p-n-diode and a Schottky diode with identical areas, both fabricated on the same HV-HBT-based layer structure as described above. However, it is measured using 50 ohms environment, thus the time constants observed in fig. 4 and fig. 5 are not the intrinsic one of the diode but given by $R*C_{diode}$, with resistance R being the sum of the 50 Ω impedances of the pattern generator and the oscilloscope and the diode resistance R_b itself. R_b denotes the dc resistance in forward direction and, depending on the diode size, varies between 2 and 3 Ω. Note that R_b is small compared to 50 ohms. Therefore, R approximates 100 ohms and one can extract the intrinsic recovery time of the diodes as R_b*C_{diode}.

While for the pn-diode a relatively long (intrinsic) recovery time of 46 ps is extracted (fig. 4), the power Schottky-type diode recovers at a much shorter time of 12 ps due to minimized charging effects in the latter case (fig. 5).

Table 1 summarizes results of time-domain measurements for the fabricated power Schottky diodes in dependence on the diode size. Very low recovery time values in the region of 9 - 12 ps were extracted for all three Schottky diode types.

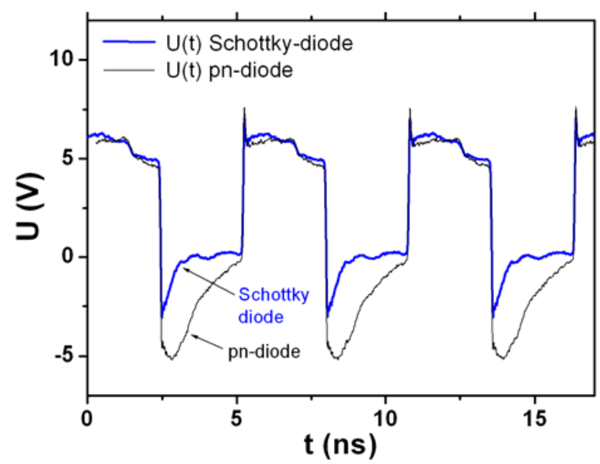

Fig. 4: Time-domain measurements giving a recovery time of 590 ps (extracted 12.1 ps for intrinsic diode) for 20 finger power Schottky diode in comparison with similar pn-diode (recovery time of 2.2 ns, extracted 45 ps for intrinsic diode) obtained with square-wave input signal of 180 MHz, V_{pp} = 13 V.

PA CIRCUIT APPLICATION

The voltage-current capabilities achieved, together with the switching speed in the ps-range, give the possibility for unique combination of the Schottky diodes with HV-HBTs in high speed MMICs. The diodes were found to be usable for switched-mode power amplifiers at data rates of 1.8 Gbps. As a first result, an HV-HBT-based gain block was fabricated operating at 18 V. This PA yielded a digital output power of 5.4 W with very high collector efficiency of 92% [5].

CONCLUSIONS

High-power, high-voltage GaInP/GaAs HBT technology has still great potential for high efficiency power applications. Especially, due to its mature technology and superior reliability high performance HV-HBT-based MMICs provide specific solutions until new wide-band-gap

technologies become really available. Thus, commercializing of HV-HBT products is still in focus [7].
Taking advantage of optimized technology the portfolio of HV-HBT-based MMICs can easily be expanded by high-power, ultra-fast switching Schottky diodes. Combined with advanced heat dissipation solutions like flip-chip mounting novel highly efficient power amplifier approaches can be realized.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
HV-HBT: High-Voltage HBT
PA: power amplifier
MIM-capacitor: metal-insulator-metal-capacitor
DC: Direct Current
std. dev.: standard deviation