

Germanium Devices: Hybrid Integration and Substrate Removal

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Abstract

In this paper we present a new technique for the hybrid integration of thin-film Metamorphic HEMTs grown on Germanium. Substrate removal is essential in this process, both to improve the performance of the devices and to facilitate the integration.

INTRODUCTION

High packaging density, large scale integration of passive and active components have become key issues in the further development of portable communication systems. Recent developments have shown that MCM-D technology may be used for the integration and interconnection of high quality microwave and RF applications [1]. A MCM-D (Multi Chip Module with deposited Dielectric layers) is a special multi-layered thin-film interconnection technology consisting of a glass substrate (wafer) with alternating dielectric and metal layers on top. IMEC has already realized various high quality passive components in this stacked configuration [2]. This hybrid integration (in contrast to monolithic integration) is often the only feasible solution because of the heterogeneity of components and the complexity of some RF systems. Besides, the automotive industry is a strong driving force to develop alternative technologies with equal performance as MMICs but lower cost. Integration of thin-film individual High Electron Mobility Transistors (HEMTs) with passive circuitry can result in low-cost advanced hybrid systems for mass-market millimeter wave applications.

DEVICE FABRICATION

Epitaxial layers for HEMTs are usually grown with Molecular Beam Epitaxy (MBE) on GaAs substrates. As reported previously [3], high performant $\text{In}_{.53}\text{Ga}_{.47}\text{As}/\text{In}_{.52}\text{Al}_{.48}\text{As}$ M(etamorphic) HEMTs can be fabricated on Germanium substrates.

The layer structure we have used for these devices had already been studied thoroughly and has resulted successfully in many circuit demonstrators, ranging from linear amplifiers (up to 94 GHz [4]) to 20 GHz frequency doublers etc.. Also the device fabrication is identical to the one developed on InP (and GaAs) over the last years. Device fabrication consists of

active area definition through wet mesa etching, deposition and alloying of Ni/Au/Ge ohmic contacts and Cr/Au c-gate metal deposition. The gate lithography is performed by E-beam to obtain a T-shaped 0.2 μm wide resist profile. After wet selective recess etch of the cap layer the Pt/Ti/Pt/Au gate metal is deposited. The processing is finished by the plasma-assisted deposition of Si_3N_4 dielectric for device passivation.

DEVICE PERFORMANCE

These devices display DC performance parameters, comparable to MHEMT structures on GaAs, even to Lattice Matched (LM) HEMTs on InP. Most significant plot is the channel current in function of the gate-source bias and the corresponding transconductance (derivative of the channel current). In Figure 1 this plot is given for a MHEMT grown on Germanium and, as expected, the curves are strikingly similar with the ones we had obtained for devices on GaAs. Maximum g_m is 720 mS/mm and maximum I_{ds} is 650 mA/mm. All measurements are performed at $V_{ds}=1\text{V}$.

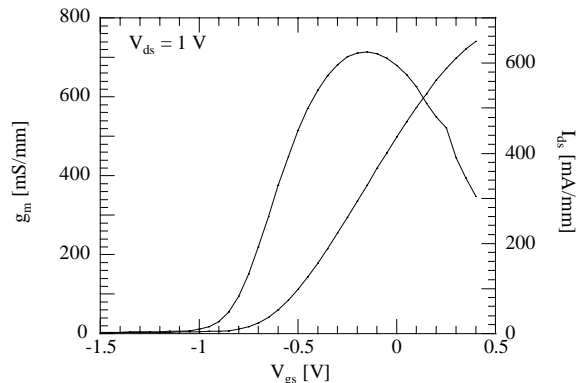


Figure 1: I_{ds} and g_m of a MHEMT on Germanium

The most important device performance comparison is in the field of high-frequency behavior. Especially the cut-off frequency f_T and the maximum oscillation frequency f_{max} are important parameters, extracted from S-parameter

measurements. In Table 1 an overview of the typical HF parameters of the devices is given. It is important to notice that these values are extrinsic values, i.e. without subtraction of parasitic extrinsic components. Although this method would reveal significant higher values is not needed for mutual comparison.

TABLE I
OVERVIEW OF EXTRINSIC HF CHARACTERISTICS

	GaAs based	Ge based (with substrate)	Ge based (substrate removed)
f_T [GHz]	90	45	70
f_{max} [GHz]	130	68	120

When comparing the HF performance of 0.2 μm gate length devices to the GaAs based ones, a large discrepancy has been revealed, as is shown in Table 1. This dramatic drop in HF performance can be attributed to the biggest limitation of the Germanium substrate: its conductivity. The devices are processed on a substrate with a limited resistivity, whereas the GaAs substrates are semi-insulating. The conductive substrate, although covered by the semi-insulating buffer, acts as a capacitor (especially under the large contact pads) and thus limits the HF performance. This conclusion is supported by the excellent DC behavior, indicating that epitaxial growth is as good as on GaAs.

To overcome this problem, there are three possible solutions:

- 1) Increase of the resistivity of the substrate (at least one order of magnitude)
- 2) Increase of the thickness of the GaAs buffer to separate device from substrate
- 3) Removal of conductive material after device fabrication

The first option requires high-purity Germanium and is too costly for competition with GaAs substrates. The E-M fields extend to typically 25 μm into the semiconductor, making buffers of this thickness necessary. For this reason, the second option is also ruled out. The third option is the most feasible with limited additional cost.

INTEGRATION AND SUBSTRATE REMOVAL

After device fabrication the Germanium wafer is diced. Then a chip is mounted on a glass 6" substrate (active side facing the glass) in a 3 μm thick spincoated polymer layer (BCB). In contrast to [3], where we used wax for the gluemounting, we switched to BCB because this polymer is often used in MCM-Ds.

Benzocyclobutene or BCB is a thermo-setting polymer with a high glass transition temperature ($T_g > 350^\circ\text{C}$) and a low dielectric constant ($\epsilon = 2.7$). Therefore this spin-on low-k dielectric is very suitable for microelectronic interconnect technology and RF integration.

The frontside of the chip is now protected by the BCB, which we use here as glue, and the MCM-D substrate, which will also serve as the carrier of the epitaxial layer after substrate removal. The gluemounting is done with a flip-chip system in thermo-compression mode but without using indium bumps for contacting. The chips we have used for the integration contained 24 transistors, also smaller chips, single transistor, are possible. After gluemounting the BCB needs thermal curing, i.e. polymerization of the BCB, for mechanical strength. This is done in an oven at 210°C.

Removal of the Ge can be done by Reactive Ion Etching (RIE) in a mixture of CF_4 and O_2 . The conditions of this dry etch method have been adapted and optimized to maintain uniformity and reduce damage of the active layers. An etch rate as high as 3-4 $\mu\text{m}/\text{min}$ can be achieved, yielding an etch time of 60 to 70 minutes for complete substrate removal. Main advantage of this plasma method is the high selectivity of Ge towards GaAs being the first epitaxial layer, i.e. nucleation layer, on top of the Ge substrate. In this way a total clearance of the Ge can be obtained in a reproducible and reliable fashion. This selectivity has not yet been determined accurately, but is estimated to be at least 100, being more than enough to stop at the GaAs. The surface of the revealed GaAs is extremely clean and smooth and therefore mirror like.

The GaAs buffer can be removed selectively in a sulfuric acid based solution, $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2/\text{H}_2\text{O}$, in approximately 7 minutes. As a final processing step, the buffer has to be removed outside the active region. To be able to do this, a lithography step has to be performed. As etchant a non-selective phosphoric acid based mixture is used ($\text{H}_3\text{PO}_4/\text{H}_2\text{O}_2/\text{H}_2\text{O}$), with an etch rate around 100 nm/min. A non-selective etchant is chosen because selectivity is not needed any more, and different layer compositions have to be etched. After this step, the c-gate metal contacts of these very thin devices, i.e. thin-film MHEMTs, ($\sim 2 \mu\text{m}$) are revealed and can be contacted by probe needles from the backside. Contacting through metallized via-holes is very straightforward with the intend to realize amplifier circuits in MCM-D technology.

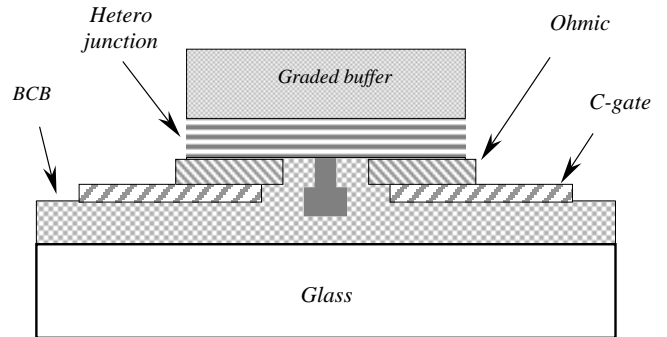


Figure 2: Cross-section of thin-film MHEMT

Moreover, to circumvent planarization problems in subsequent MCM-D processing steps, the thickness of the device has to be less than 5 μm . So, substrate removal is a solution for both of these problems. Figure 2 and Figure 3 show a schematic cross-section and a photograph of a thin-film MHEMT on a MCM-D substrate. The photograph clearly shows the metal contact pads (Source, Drain and Gate) which are revealed after the etching.

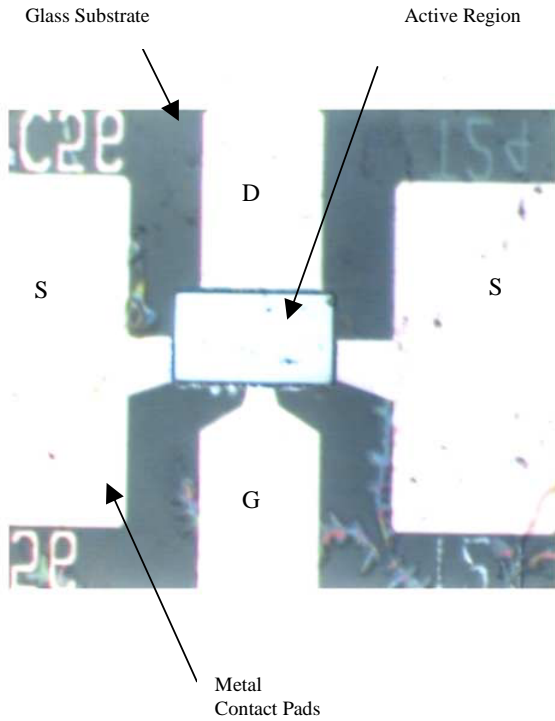


Figure 3: Photograph of a thin-film MHEMT on glass

PERFORMANCE AFTER SUBSTRATE REMOVAL

In Figure 4 the transconductance curve for the metamorphic device, based on a Germanium substrate after removal of this substrate is depicted. If we compare Figure 1 and 4, we can see that the DC performance has decreased on several fields; both saturation current and maximum transconductance have been reduced slightly. I_{ds} reaches maximum values of just over 600 mA/mm, still being a good value. The maximum transconductance has dropped to a value of 675 mS/mm. Additionally to these degradations, a tail in the I_{ds} curve is introduced. In this stage it is not determined whether this is a consequence of the substrate removal (plasma damage, no backside passivation...) or just a peculiarity, keeping in mind that little optimization has

taken place and further runs have to be processed to determine the origin of these effects.

Already in this stage it is foreseen that disposal of generated heat might become a problem after thinning and complete isolation of the semiconductor material.

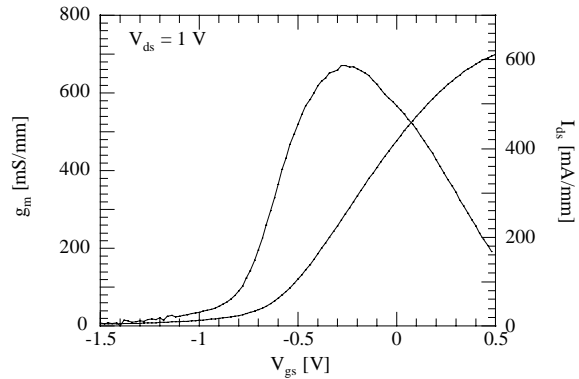


Figure 4: I_{ds} and g_m of a thin-film MHEMT on glass

A more significant performance comparison has to be made in the field of high-frequency behavior. Before substrate removal the cut-off frequency and the maximum oscillation frequency were $f_T = 45$ GHz and $f_{max} = 68$, respectively. Remeasuring these parameters on glass MCM-D wafers (after removal of the Ge) resulted in $f_T = 70$ GHz and $f_{max} = 120$ GHz. These results are shown in Table 1. These (extrinsic) values show that the conductivity of the substrate is responsible for most of the reduced performance of Ge based devices and that this problem can be overcome largely by removing the substrate material. Figure 5 shows the current gain (H_{21}) of such a thin-film MHEMT in function of frequency.

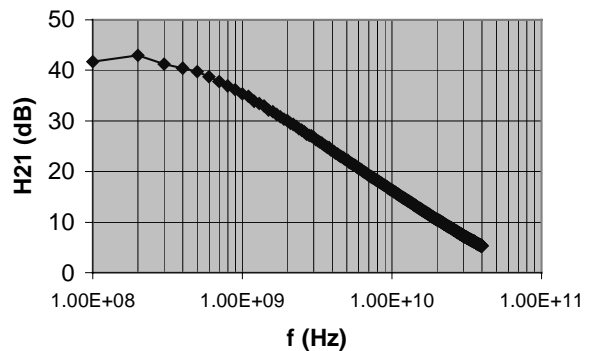


Figure 5: H_{21} of a thin-film MHEMT in function of frequency

CONCLUSIONS

To yield way to integration of Ge MHEMTs in low-cost MCM-D substrates, a highly selective method for substrate removal is presented. Integration in MCM-D substrates (either passive or active devices) is only possible for thin devices, i.e. less than 5 μm . Moreover, the performance of MHEMTs on Germanium substrates can be improved dramatically (60% higher f_T) with the removal of the conductive Germanium, although a 10% DC degradation is observed. Combined with the low environmental load of this method, the presented process provides with a high performance technology ready for advanced hybrid integration.

Future work will be focused on the realisation of transimpedance amplifiers or narrow-band high-gain amplifiers in this hybrid MCM-D technology, as opposed to [4] where MMICs based on GaAs MHEMTs have been presented.

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