# SYSTEMATIC INVESTIGATIONS ON MESFETS AND PASSIVE COMPONENTS TRANSPLANTED BY EPITAXIAL LIFT OFF ONTO HOST MATERIALS WITH VARIOUS RESISTIVITIES

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## Abstract

In this paper we present RF measurements on MESFETs and spiral inductors fabricated on GaAs and transplanted by epitaxial lift off (ELO). ELO is a technology by which epitaxially grown layers are lifted off from their growth substrate and are subsequently re-attached to a new host substrate.

## Introduction

ELO allows the monolithic integration of incompatible materials such as GaAs and InP or GaAs and Silicon [1]. This paper represents the first systematic study on the RF characteristics of active and passive devices transplanted by ELO onto host materials with various resistivities. Host materials considered are quartz, InP and Si with resistivities between 11 mΩcm and 50 Ωcm. This is also the first time RF-investigations are reported on MESFETs which were transplanted onto silicon using the *postprocessing* method [2]. No reports on ELO transplantation of MESFETs onto quartz can be found in literature either.

Devices performance is compared before and after transplantation. In addition RF characteristics as a function of substrate conductivity is presented.

## Epitaxial lift off

GaAs MESFETs were fabricated using the slightly modified D07A foundry process offered by Philips Microwave Limeil, France. This process offers depletion mode MESFETs with a gate length of 0.7 µm as well as resistors, capacitors and Schottky diodes. The modification concerns the wafer materials. The material required for ELO was epitaxially grown. In order to make ELO possible, a 50 nm thick sacrificial AlAs layer was grown 800 nm below the surface of the wafer. On top of this AlAs layer a 600 nm thick semi insulating GaAs layer and a 200 nm thick n-doped GaAs layer were grown. The latter one will form the channel of the MESFETs. The AlAs layer is the only non-standard step, but is necessary for chemical lift-off. The growth of the AlAs layer is simple since it is lattice matched to GaAs. These wafers were then used to build test devices processed by the standard foundry process. The completely processed chips were now transferred by the ELO process onto various substrates materials.

Access to the buried AlAs layer is either obtained by cleaving the chips or by introducing dry etched trenches between the chips. Since the ELO layer thickness is only 800 nm, a 300 µm thick wax layer is deposited to provide protection and mechanical support during transfer [2, 3]. The sacrificial AlAs layer is undercut by an extremely selective etchant (10:1 diluted HF). A slight surface tension in the wax layer causes an upwards-curling of the film during the etching of the AlAs-layer, thus enhancing the etching process. The ELO-film is then released from its growth substrate and can

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be subsequently attached to an arbitrary host substrate, such as InP, quartz $LiNbO_3$ or Si. Bonding is assured by Van der Waals forces.

An excellent morphology can be obtained when the transfer of the film is performed under water. In this so-called "underwater processing", the ELO-film is etched, rinsed and subsequently attached to the host without leaving the de-ionized water. The "underwater processing" is used to avoid contamination of the lower surface of the film. The transfer itself is performed using micromanipulators and can be observed through two microscopes while the ELO devices are underwater. One microscope shows the ELO film from the top enabling accurate placing. The second microscope is mounted from the side helping with the landing of the film. To enhance adhesion to the host material a 300 nm polyimide layer (Dupont-Pyralin 2555) was deposited to the host material by spin coating prior the transplantation. This layer planarizes substrate irregularities.

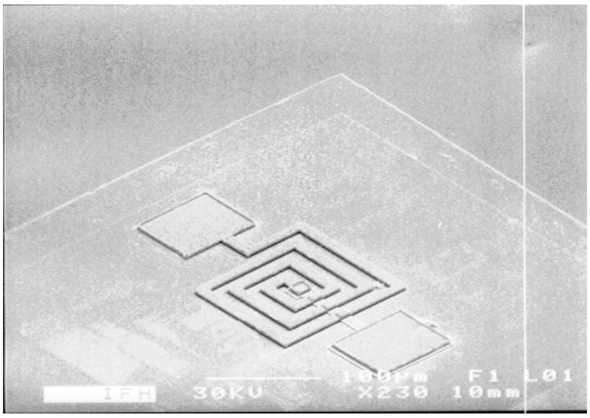


Fig. 1 SEM photograph of an 800 nm thick GaAs film transplanted onto silicon by epitaxial lift off (pads 80 μm by 80 μm).

Once the film is bonded onto the host, the sample which is still wax coated is placed under a weight for approximately one day allowing excess water to diffuse towards the edges and evaporate. After the removal of wax with trichlorethylene the samples are baked-out in order to improve their bonding strength.

Fig. 1 shows an SEM photograph of an ELO film containing a spiral inductor after transplantation onto silicon.

**Measured RF performance of transplanted MESFETs**

On wafer S-parameter measurements have been performed before and after ELO. In the case of a lossy substrate, the pad capacitances need to be extracted and de-embedded. Fig 2 shows $S_{11}$ and $S_{22}$ of a de-embedded 0.7x4x50 μm MESFET before and after transplantation onto Si.

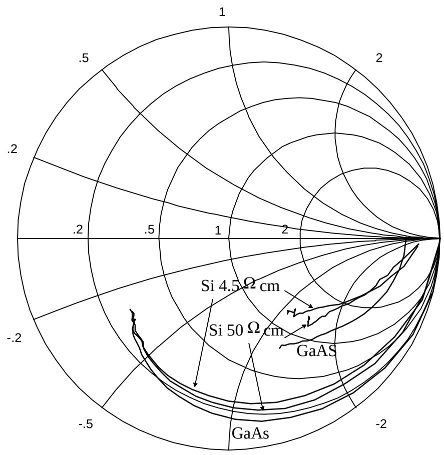


Fig. 2 $S_{11}$ and $S_{22}$ of 0.7x4x50 μm MESFETs transplanted onto silicon with resistivities of 4.5 and 50 Ωcm. For comparison a typical device before transplantation is also shown. Frequency range 45 MHz to 26 GHz. Bias: $V_{ds}$ = 3 V, $I_{ds}$ = 11 mA, $V_{gs}$ ≈ -0.75V.

Fig. 3. shows the short circuit current gain ($h_{21}$) of the same devices transplanted onto silicon and quartz. Fig. 4 shows $f_T$ and $f_{max}$ as a function of substrate resistivity. Devices were transplanted onto Si, InP [4,5] and quartz. The performance reduction due to a transplantation onto silicon even with rather low resistivities, as it is used in a typical CMOS process, is modest.

Intuitively one would expect $f_T$ and $f_{max}$ to decrease with decreasing substrate resistivities. Remarkably no significant penalty due to the low substrate resistivity is observed for resistivities as low as 5 Ωcm. RF measurements of ELO transplanted MESFETs onto silicon was previously only reported using the *prepro-*

*cessing* method [6] with a thick $SiO_2$ or $Si_3N_4$ layer as a spacer between the conductive silicon and the GaAs film. Oxides with a thickness above 1 µm are however time consuming to grow. As these experiments show, polyimide (PI) can be used to replace silicon dioxide. PI can be applied with spin coating in thicknesses up to several microns. In addition it can easily be patterned. For this application PI is therefore an attractive alternative to $SiO_2$.

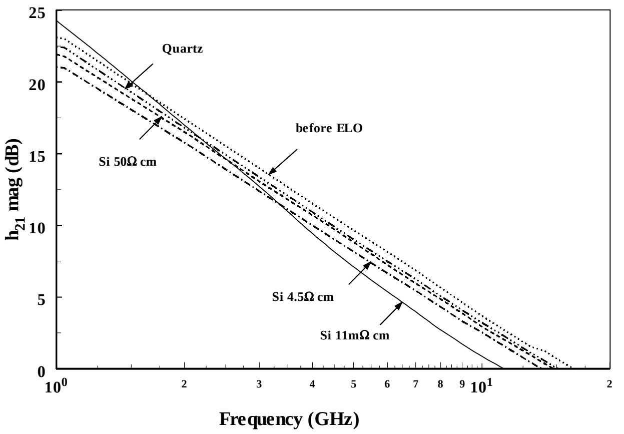


Fig. 3 Short circuit current gain $h_{21}$ for 0.7x4x50 µm MESFETs before and after ELO. Devices were transplanted onto silicon of various resistivity and onto quartz. Bias: $V_{ds}$=3V, $I_{ds}$=11 mA, $V_{gs}$≈-0.75V.

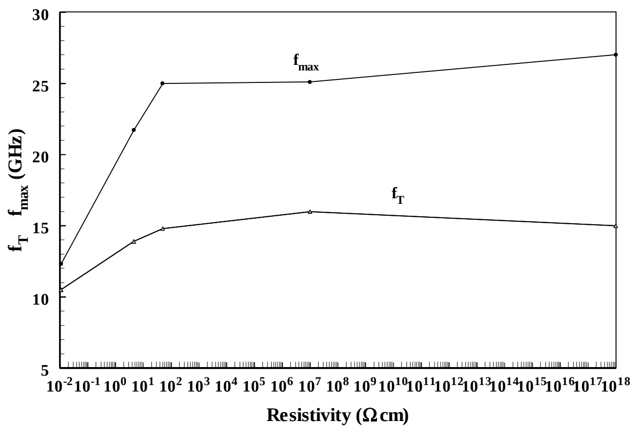


Fig. 4 $f_T$ and $f_{max}$ of ELO transplanted MESFETs as a function of substrate resistivity. (Devices: 0.7x4x50 µm)

## Spiral inductors transplanted by ELO

The effects of ELO on passive components are hardly considered in literature. Since large devices are more effected by substrate losses, spiral inductors were chosen to investigate the effects of ELO transplantation. After transplantation onto silicon, the pads significantly contributed to the RF loss due to their large area. For this reason pads on all materials considered were measured separately. By subtracting the $y_{11}$ parameter of the pads from the $y_{11}$ parameter of the spiral, the de-embedded spiral was determined. Fig. 5 shows the imaginary part of the input impedance of a 2.3 nH spiral inductor before and after transplantation. (Spiral size: 115 µm x 115 µm, 5 µm conductor, 5 µm spacing, 5 turns).

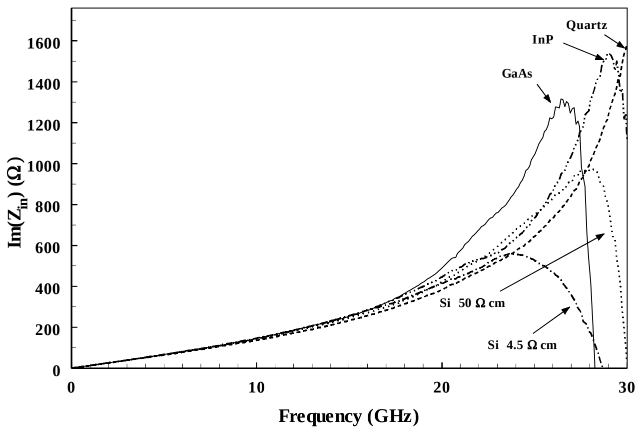


Fig. 5 Imaginary part of the input impedance of a 2.3 nH spiral inductor before and after transplantation onto various materials.

The first parallel resonance of the spiral inductor is clearly visible. A transplantation onto conductive silicon (ρ 4.5 Ωcm) will reduce the resonance by 3 GHz due to the increased parasitic capacitance to the substrate material. On the other hand, a transplantation onto InP or quartz increases the resonance frequency. This is not alone explainable by the smaller dielectric constant of InP and quartz as compared to GaAs but also by the addition of 300 nm PI with a dielectric constant of only 3.5 that is located below the GaAs film. This leads to a reduction in parasitic capacitance, especially noticeable in spirals transplanted onto quartz. The spiral transplanted onto lightly doped silicon also

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shows an increased resonance frequency. This shift is reproducible and caused by reduced parasitic capacitance due to the PI and the lower dielectric constant of silicon as compared to GaAs. ($e_{r\,Si}$ = 11.7, $e_{r\,GaAs}$ = 13.1).
Fig. 6 shows the Q factor defined as:

$$Q = \frac{Im(Z_{in})}{Re(Z_{in})}$$

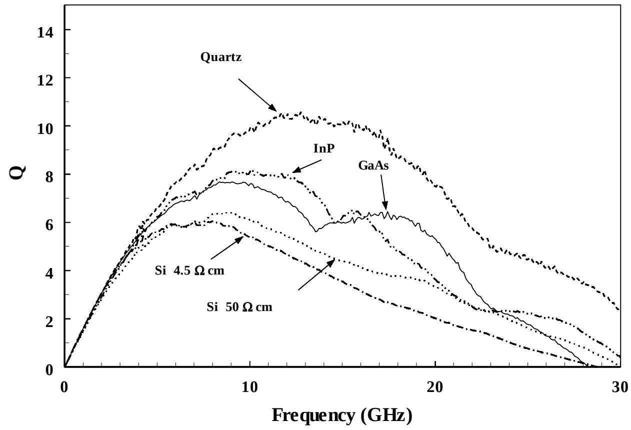


Fig. 6 Q factor of an 2.3 nH spiral inductor before and after transplantation onto various materials.

A transplantation onto quartz will result in a 25% increase in Q. This can easily be explained with the smaller dielectric loss of quartz as compared to SI-GaAs. A transplantation onto InP results in no significant change where as a transplantation onto silicon increases the loss. Higher doped silicon will result in higher loss.
However, a transplantation onto silicon, even highly doped silicon of 4.5 Ωcm as it is used in a commercial BiCMOS process, will only reduce the Q by about 25%. This also for a fairly large spiral inductance of 2.3 nH measuring 115 μm x 115 μm.

## Conclusions

In this paper the first systematic study on MESFETs and passive components transplanted by ELO onto substrates with various resistivity is presented. A transplantation of MESFETs onto silicon will result in only a small reduction in the RF performance despite the low resistivity of the host material. A substrate resistivity down to a few Ohm-centimeter is tolerable. Such substrate resistivities are used in commercial CMOS or BiCMOS processes. Passive components like large spiral inductor will also exhibit only a small reduction in their RF Q. Thus the transplantation of RF circuit blocks such as RF frontends on a larger CMOS integrated circuit is feasible. This technique would allow the integration of the high speed components of a receiver in GaAs and the low speed component in a low cost CMOS process. Using ELO the two chips can be *monolithically integrated* thus avoiding selective growth of GaAs on Si.

## References


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