MEMBRANE SUPPORTED MILLIMETER WAVE CIRCUITS BASED ON SILICON AND GaAs MICROMACHINING

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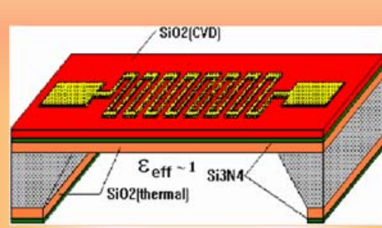
Why membrane supported millimeter wave circuits?



Advantages of membrane-supported passive circuit elements

- reduction of losses due to the dielectric substrate
- reduction of dispersion effects
- the structure looks like being "air suspended" (ε_{eff} ~ 1)
- suppression of unwanted substrate modes
- new features for the design of integrated subsystems

Membrane Supported Circuits for Millimeter Wave Applications (obtained by silicon micromachining)

First Results-obtained by micromachining of h. r. <100> silicon

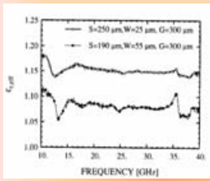
Ann Arbor Univ., Michigan, USA (***L. Katehi, G. Rebeiz et.al.*****)**:

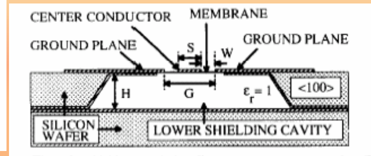
- micro-shielded structures (starting from 1991)
- lumped elements and antennas (starting from 1992)

1996-1997

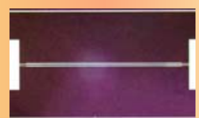
- LAAS/CNRS, Toulouse
- IMT Bucharest and CNR Rome
- IRCOM Limoges

ε_{eff} determination



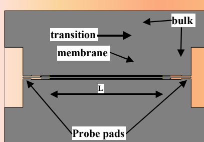


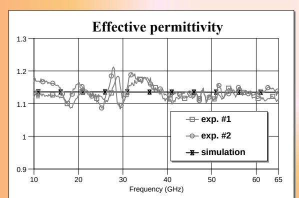
Experimental determination of ε_{eff} for the microshilded CPW line (T. Weller, L. Katehi, G. Rebeiz, IEEE Tr on MTT, vol. 43, p. 534, 1995)



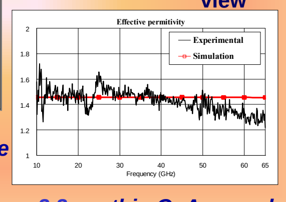
Experimental test strucure (s = w = 40µm; L_1=3900 µm; L_2=3600 µm) - top view

our results





1.4 µm thin SiO_2/Si_3N_4 membrane



2.2 µm thin GaAs membrane

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Technology

- high resistivity <100> oriented silicon substrate
- CrAu or TiAu deposition, patterning and selective gold electroplating; definition of the back side etching areas by double-side alignment
- silicon backside etching (wet, DRIE, dry+wet...)

One of the key elements is the membrane layer

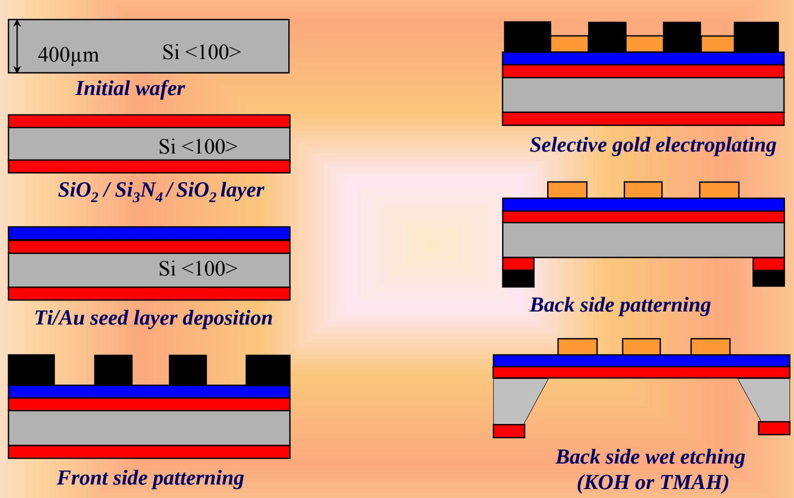
$SiO_2/Si_3N_4/SiO_2$ layer with a total thickness of 1.4 µm (0.7/0.3/0.4)

- first proposed by the group of G. Rebeiz and L. Katehi et al. from Ann Arbor Univ. Michigan (1991). This sandwich has a slight tensile stress, to yield flat and self-supporting rigid characteristics.

SiO_2/Si_3N_4 layer with a total thickness of 1.4 µm (0.8/0.6)

- first proposed by E. Saint Etienne et al [E. Saint Etienne, P. Pons, G. Blasquez, P. Temple, V. Conedera, M. Dilhan, X. Chauffleur, Ph. Ménini, R. Plana, T. Parra, B. Guillon, J.C. Lalaurie, *Sensors and Actuators A*, vol. 68/1-3, pp. 435-441 (1998)]

Membrane supported circuits manufacturing using "classical" wet backside etching process



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Electromagnetic simulations

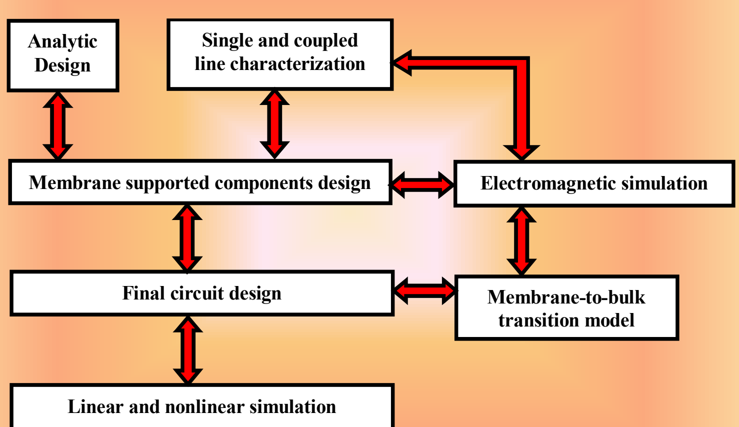
- **IE3D** Zeland Software Inc., Freemont, CA, full wave, Method-of-Moments simulator
- performs electromagnetic analysis for arbitrary 3-D planar geometry maintaining full accuracy at all frequencies.
- the electromagnetic analysis includes dispersion, discontinuities, surface waves, higher order modes, metallization loss and dielectric loss
- optimization engine that allows the using of multiple objective function optimization variables are the main layout dimensions

IE3D Zeland software package

- **based on open boundary Green's functions formulation**
- **well-matched for the modelling of filter and antenna structures without metallic enclosures**
- **the structure is divided into the membrane supported circuit block and the bulk supported circuit block**

Membrane supported circuits – Design

Design flowchart



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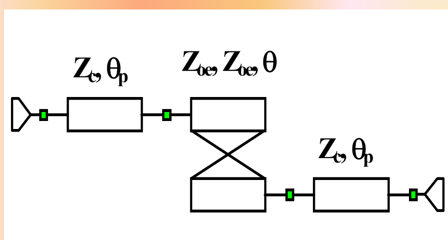
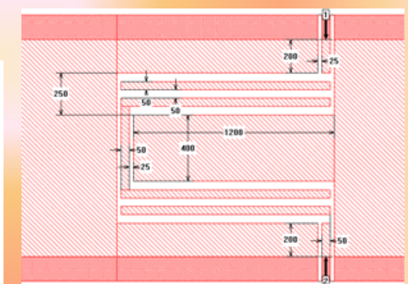
New type of coupled line filter

•**Conventional design** is based on an exact or approximated frequency transformation to obtain the distributed network starting from a lumped element prototype

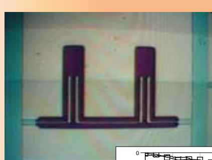
•**New approach**: the design starts directly from a distributed structure consisting in identical symmetric cells connected in cascade and the filtering properties of the network is studied by the image parameter representation of the two-port networks

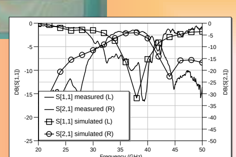


Elementary cell used for the filter design



Micromachined Millimeter Wave Filter Structures Supported on 1.5 µm $SiO_2/Si_3N_4/SiO_2$ Membrane on Silicon Substrate

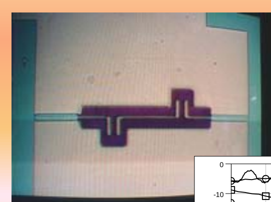


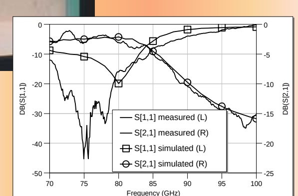


On wafer measurements for the 38GHz grounded coplanar waveguide filter supported on $SiO_2/Si_3N_4/SiO_2$ membrane

38 GHz filter

- ♦ **Minimum insertion loss: 1.9 dB**
- ♦ **Maximum return loss: 16.5 dB**





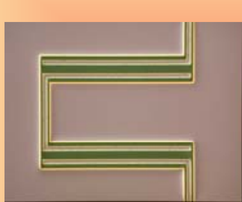
On wafer measurements for the 77GHz grounded coplanar waveguide filter supported on $SiO_2/Si_3N_4/SiO_2$ membrane

77 GHz filter

- ♦ **Minimum insertion loss: 1.5 dB**
- ♦ **Maximum return loss: 44.5 dB**

A.Müller, C. Constantinidis, F. Giaccomozzi, M. Lagadas, G. Deligeorgis, S. Iordanescu, I. Petrini, D. Vasilache, R. Marcelli, G. Bartolucci, D. Neculoiu, C. Buiculescu, P. Blondy, D. Dascalu J. Micromech. Microeng. 11 (2001) pp1-5

45 GHz Membrane supported filters



Top and bottom view

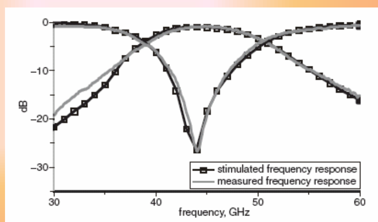


Fig. 3 *Simulated and measured frequency responses for bandpass filter fabricated using silicon micromachining*

D. Neculoiu, G. Bartolucci, P. Pons, L. Bary, D. Vasilache, A Müller , R. Plana, Electronics Lett, vol 40, pp.180-182, 2004

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The state of the art

Membrane supported antennae structures:

- first micromachined antenna, a dipole: ***Rebeiz, Kasilingam, Stimson, Rutledge, 1990***

- tappered slot antennae***: Ekstrom, Gerhart, Acharya, Rebeiz, Colberg 1992***

- microstrip antennae: ***Gauthier, Raskin, Katehi, Rebeiz 1999***

- folded slot antennae for 77 and 94 GHz: ***Neculoiu, Pons, Plana, Blondy, Vasilache, Muller 2001***

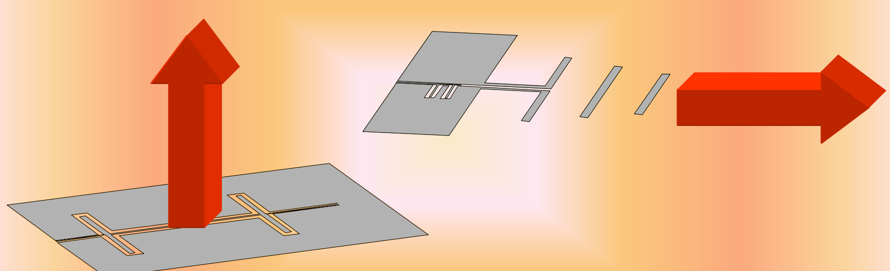
- folded slot antennae in a hybrid integrated receiver for 38 GHz: ***Muller, Neculoiu, Marcelli, Bartolucci, Giacomozzi, Petrini, Buiculescu,Vasilache, Dragoman, Avramescu, Dascalu, Zen, 2002***

- folded slot antennae in a monolithically integrated receiver for 38 GHz on GaAs membrane: ***Konstantinidis, Neculoiu, Lagadas, Deligiorgis, Vasilache, Muller, 2003***

- Yagi-Uda membrane supported antennae: ***Neculoiu, Pons, Vasilache, Bary, Muller, Plana, 2003***

Types of planar antennas

End-fire radiation pattern



Broadside radiation pattern

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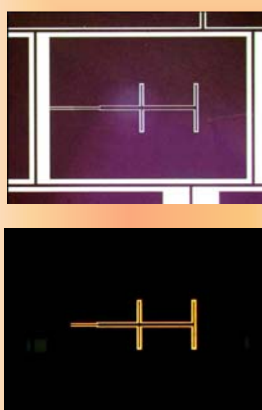
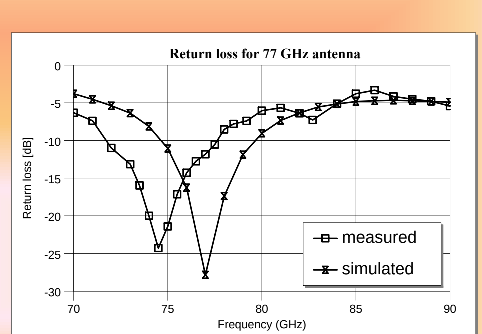
Design approach

1. **Analytical estimation** of the main layout dimensions at the central operating frequency (because the structures look being "air suspended", these dimensions are usually expressed in term of free-space wavelength)
2. Optimization of the antenna performances in terms of radiation pattern, antenna gain and reflection losses using **intensive electromagnetic simulations**
3. Manufacturing and testing of the membrane-supported antenna demonstrators
4. Design and optimization of the antenna structures for a given application, integrated with other circuit element into a receiver or transmitter front-end.

Membrane supported antennas for 77 GHz - 2001



Top and bottom view (with top illumination)



Measured and simulated return loss for the 77 GHz antenna structures

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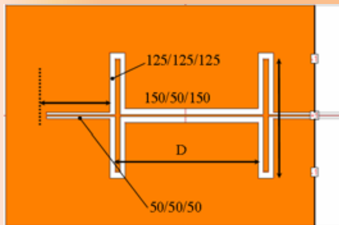
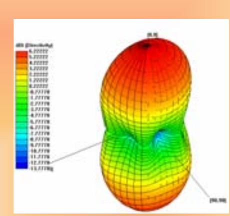
Double folded slot antenna for 35 GHz

IMT-LAAS 2003

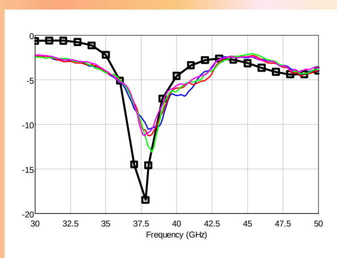


Directivity: 6.22 dBi

Gain: 3.32 dBi



Simulation results: 3D Radiation pattern



Simulated and measured return losses

Yagi-Uda membrane supported antenna

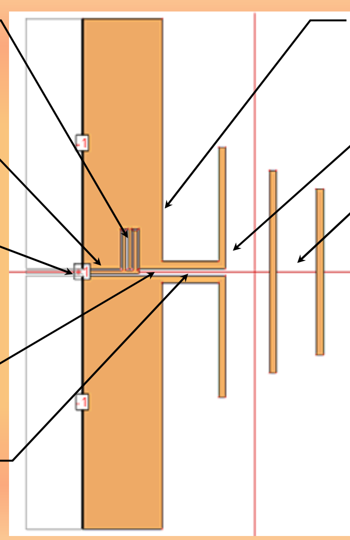
CPW to slotline transition

CPW line

Differential port

Slotline

Coplanar strips (CPS)



Truncated ground plane reflector

Driver dipole

2 directors

Direction of radiation

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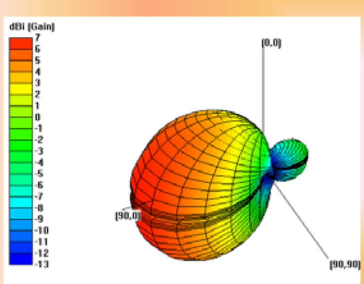
Design steps

- scaling a high performance UHF version Yagi-Uda antenna to 45 GHz operating frequency
- optimization of the Yagi-Uda structure with truncated ground plane for optimum radiation pattern at 45 GHz using Zeland IE3D simulation software
- design of the feeding network and CPW-CPS transition using IE3D electromagnetic simulations
- final optimization of the overall membrane supported structure

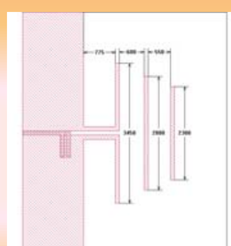
Simulation results

45 GHz

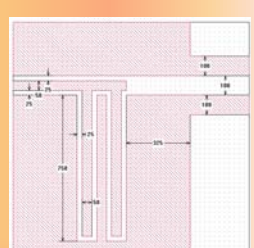
λ_o = 6.666 μm



3D radiation pattern at 45 GHz



Yagi-Uda antenna final layout



CPW to CPS transition layout

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Topology requirements – technological processes

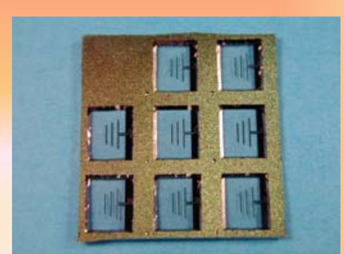
- The topology requirements are different compared with those for the filter, as well as for the broadside antennae structures due to the endfire radiation characteristic .

-A relatively thick bulk silicon wall, existing in the main direction of radiation, can affect the radiation performances of the antenna

-Yagi-Uda antennae structures were manufactured using three different backside etching processes

-New technologies, which can avoid the remaining of a thick bulk silicon wall in the main radiation direction of the antenna, have been developed

Top and bottom view of Yagi antennae structures manufactured using classical wet backside etching processing



***Major advantage*: high reproductibility, high yield**

***Major drawback*: a thick bulk silicon wall sorrounds the structure and has an major effect on the propagation**

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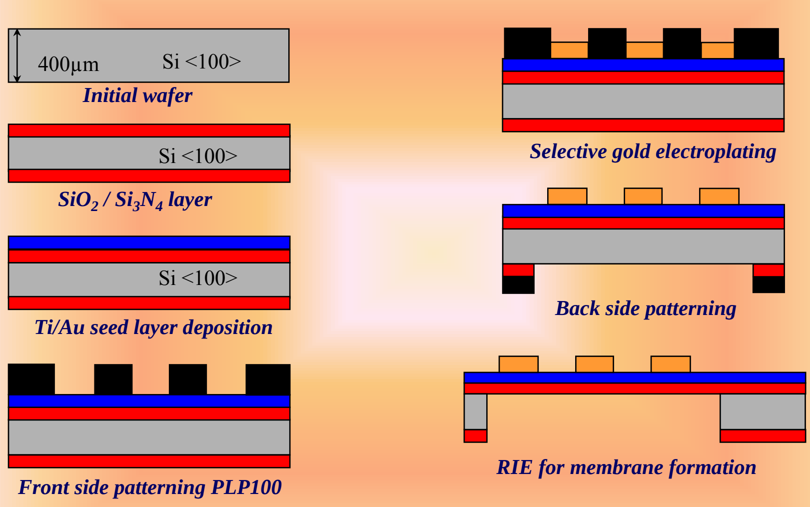
Antenna manufacturing using dry back-side RIE process



Front and backside view of membrane supported Yagi antennae using dry (RIE) backside etching process

Major advantage: only a very thin bulk silicon wall, of about 50 µm width, remains in the main radiation direction of the antenna

Major drawback: the relative low yield

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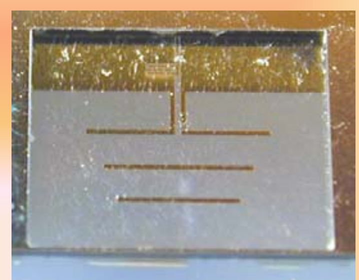
Top view

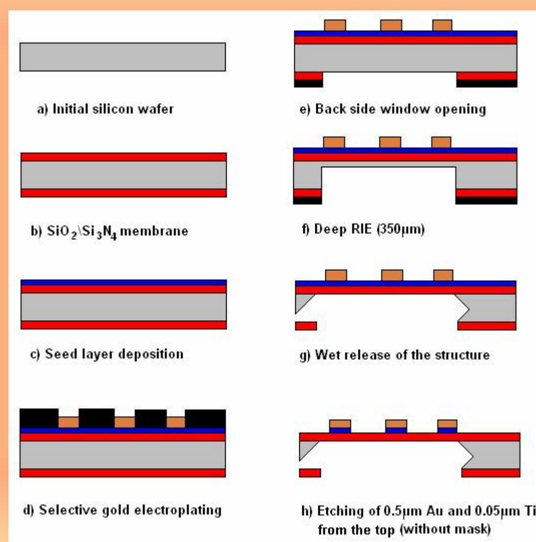
Bottom view



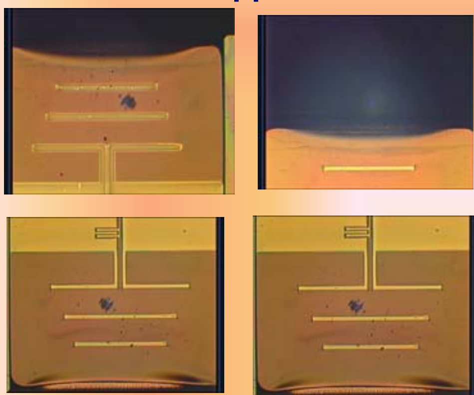
RIE backside etching process: the width of the bulk silicon for the main direction of radiation was reduced to only 50 µm

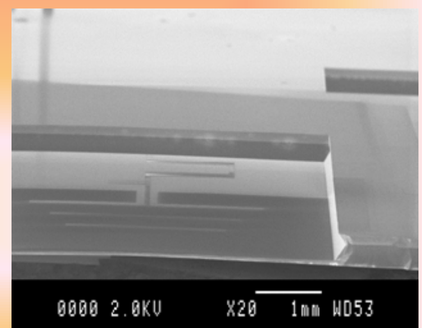
D.Neculoiu, P. Pons, L. Bary, M. Saadaoui, D. Vasilache, K. Grenier, D. Dubuc, A. Müller and R. Plana *IEE Microwave, Antennas and Propagation, Vol 151, No. 4, August 2004, pp.311-314*

Antenna manufacturing using dry followed by wet back side etching process



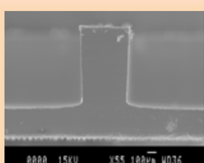
Bottom view of « quasi three edges » membrane supported antennae structures



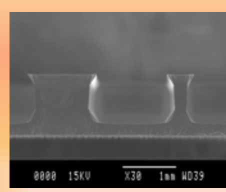


SEM Photo of the "quasi three edges" membrane supported antenna

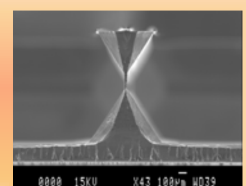
M. Saadaoui, P. Pons, R. Plana, L. Bary, P. Dureuil, D. Bourrier, D. Vasilache, D. Neculoiu, A. Müller "Dry followed by wetbackside etching processes for micromachined endfire antennae" Journal of Micromech. Microeng., vol.15, Nr7, pg. S65-S71, 2005

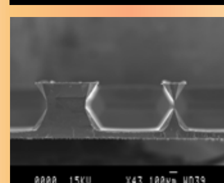


Etching profile after 300µm DRIE

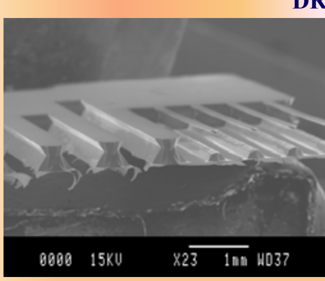


Etching profile after 300µm DRIE+15 min KOH

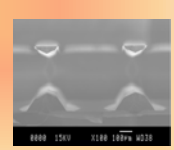




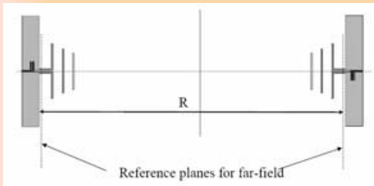
Etching profile after 300µm DRIE + 40min KOH



Membrane formation

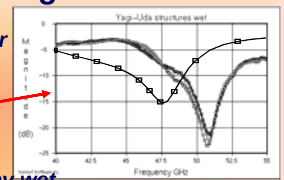


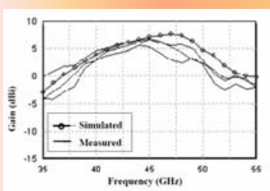
On wafer gain measurements for the Yagi Uda antenna



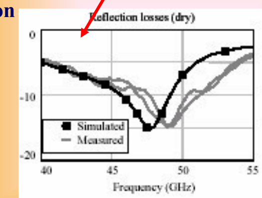
The experimental set-up used for the antenna characterization

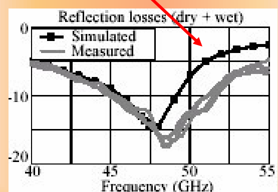
Comparative on wafer reflection losses measurements for
a) wet
b) dry
c) dry followed by wet
backside etched membrane supported antennae structures





Experimental and simulated gain of the Yagi-Uda antenna structure vs. frequency





Friis formula $G^2 = |S_{21}|^2 \left(\frac{4\pi (R+x)}{\lambda_o} \right)^2$

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  - Membrane supported filters
  - Membrane supported antennae
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  - Monolithic integrated millimeter wave receiver structures (with folded slot and Yagi-Uda antennae)
- Developments in progress
- Conclusions

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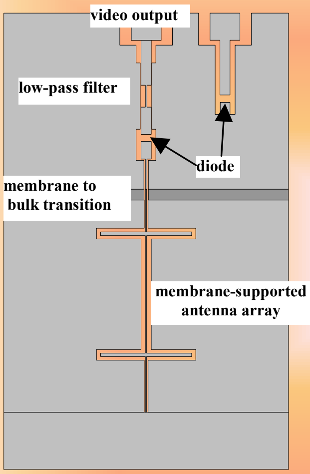
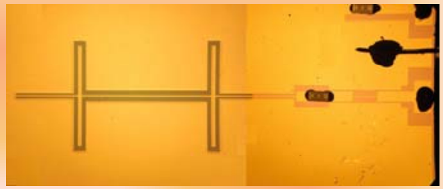
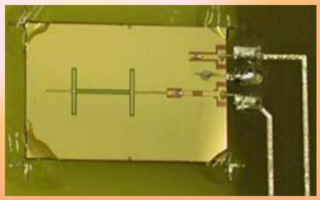
38GHz Hybrid Integrated Receiver Module



The final layout of the hybrid receiver module for 38 GHz

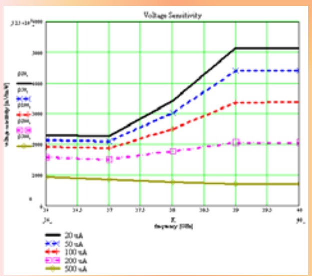


The 38 GHz receiver structure with the Schottky diode mounted

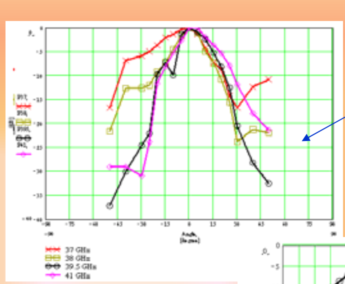


The 38 GHz receiver structure with the Schottky diode mounted

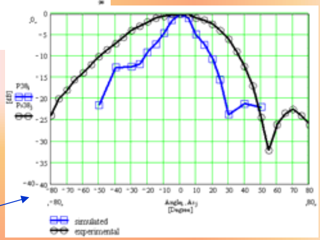
38 GHz Hybrid Integrated Receiver



Voltage sensitivity



Experimental data for radiation pattern (E plane) at several frequencies: 37, 38 , 39.5 and 41 GHz



Comparison between experimental and simulated radiation pattern at 38 GHz (E plane)

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CONTENTS

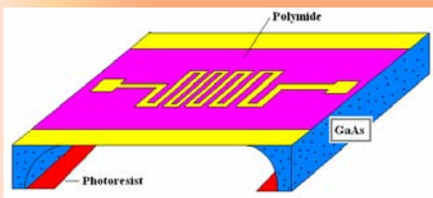
GaAs Micromachining

First micromachining process of GaAs : B. Hök, ASEA, Sweden, 1983

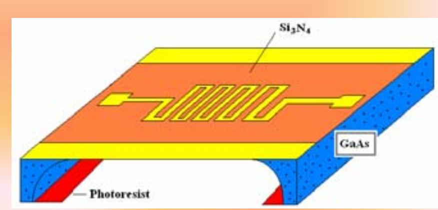
First Applications:

- ♦ *Sensing elements for high temperature applications: 1990*
- ♦ *Microwave power sensing elements (1994 - 1996) Darmstadt Univ.*
- ♦ *Membrane supported millimeter wave circuits:*
  - •Substrateless Schottky diodes for THz applications (*Darmstadt University, 1999-)*
  - • Polyimide membrane on GaAs micromachined substrate supported CPW's lumped elements (*Darmstadt Univ., IMT Bucharest & FORTH Heraklion*, 1998 - 1999)
  - •GaAs membrane supported Schottky diodes in micromachined multiplier structures for the THz frequency range (*P.Siegel et.al, Caltech Pasadena*, 1999-)
  - •GaAs membrane supported filters and receiver structures (*IMT Bucharest & FORTH Heraklion*, 2000-)

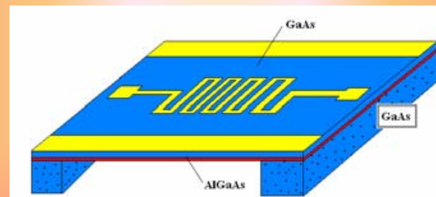
Micromachining of GaAs for membrane supported millimeter wave circuits



Polyimide membranes on GaAs substrate

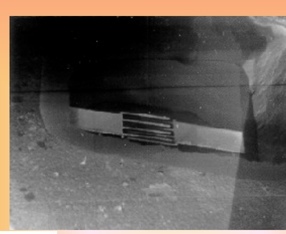


Plasma enhanced CVD Si_3N_4 membrane on GaAs substrate

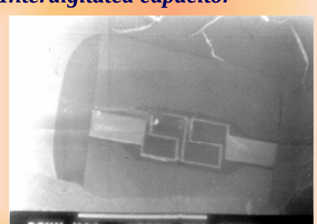


GaAs membranes obtained by selective etching technique
($Al_xGa_{1-x}As$ is an etch stop layer for GaAs if $x > 0.5$)

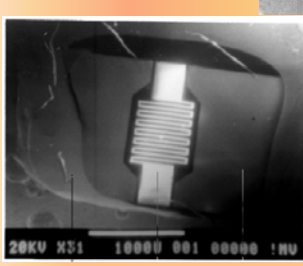
Circuit elements supported on Polyimide Membrane on GaAs substrates



Interdigitated capacitor



S line inductor



Meander inductor

A. Müller, S. Iordanescu, I. Petrini, V. Avramescu, G. Simion, D.Vasilache, V. Badilita, D. Dascalu, G. Konstantinidis, R. Marcelli, G. Bartolucci, "Polyimide based GaAs micromachined millimeter wave structures", "Journal of Micromechanics and Microengineering", 10(2000), pp.130-135.

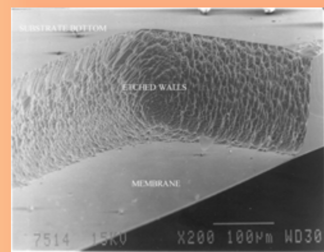
CONTENTS

Technology of GaAs membrane supported filters

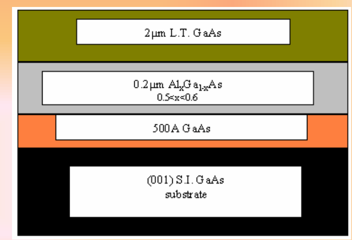
- ◆ semi-insulating GaAs substrate (>10^7 Ω cm)
- ◆ MBE growing of 0.2 µm thick $Al_x Ga_{1-x} As$ (x >0.5) etch stop layer
- ◆ LT semiinsulating thick GaAs layer (about 2 µm thick)
- ◆ resist deposition
- ◆ metal deposition by lift off
- ◆ thinning of the wafer by lapping
- ◆ backside mask; reactive ion etching (RIE) for membrane formation

GaAs membranes as support for millimeter wave filters

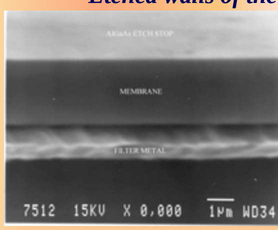
FORTH-IMT



Etched walls of the structure



The AlGaAs/GaAs heterostructure



SEM photo of the membrane, detail
(the membrane is metalized on the top)

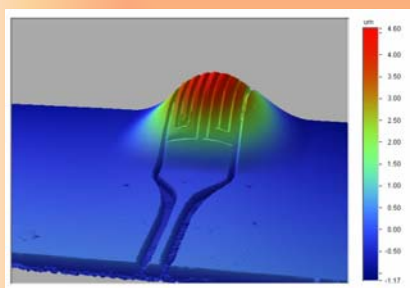
Stub filter structures on GaAs membranes

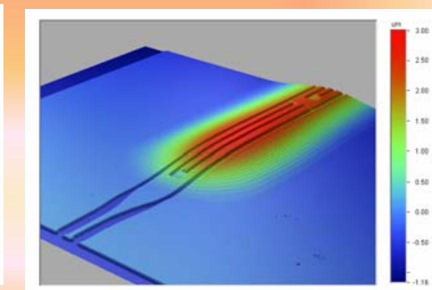
IMT Bucharest- FORTH Heraklion in the MEMSWAVE Project -2001

SEM photo of 77 GHz cascaded open end series stubs CPW filter on GaAs membrane

GaAs membrane supported double folded open end series stub band pass filter structure for 38 GHz

White ligth interferometry analysis





Millimeter Wave Filters for 38 and 77 GHz obtained by micromachining of GaAs

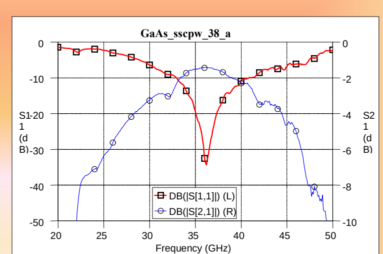
Dimensions of the membrane are 2mm x 6 mm

.

WLI analysis developed at Angstrom labs. Uppsala University

38 GHz Band-pass Filter Supported on Thin GaAs Membrane

Detail of the 38GHz 4-cell opposited open-end series stub CPW filter structure supported on a 2.2 µm GaAs/AlGaAs membrane



S parameters measurement for the 38GHz opposite open-end series stub CPW filter.

- ♦ **Minimum insertion loss: 1.46 dB**
- ♦ **Maximum return loss: 34.2 dB**

On wafer Measurements were performed at IRCOM Limoges

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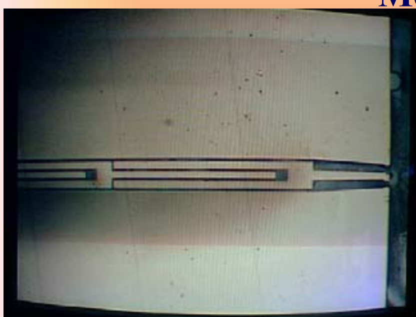
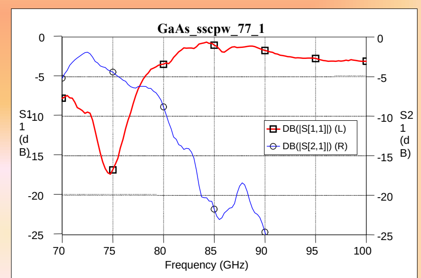
77 GHz Band-pass Filter Supported on Thin GaAs Membrane



Detail of the 77GHz 4-cell cascaded open-end series stub CPW filter structure



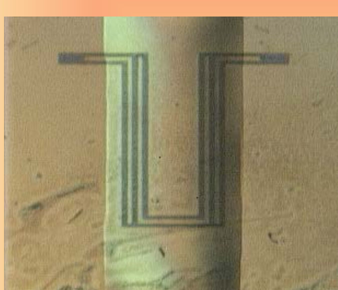
S parameters measurement for the 77GHz cascaded open-end series stub CPW filter.

- ♦ **Minimum insertion loss: 1.87 dB**
- ♦ **Maximum return loss: 17.4 dB**

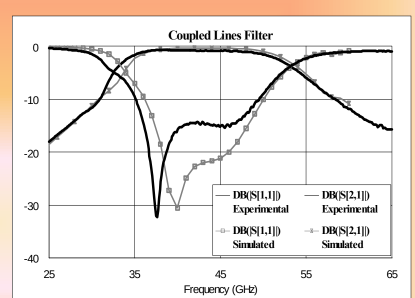
A.Müller, C. Constantinidis, F. Giaccomozzi, M. Lagadas, G. Deligeorgis, S. Iordanescu, I. Petrini, D. Vasilache, R. Marcelli, G. Bartolucci, D. Neculoiu, C. Buiculescu, P. Blondy, D. Dascalu J. Micromech. Microeng. 11 (2001) pp1-5

On wafer Measurements were performed at IRCOM Limoges

New coupled lines GaAs membrane filter



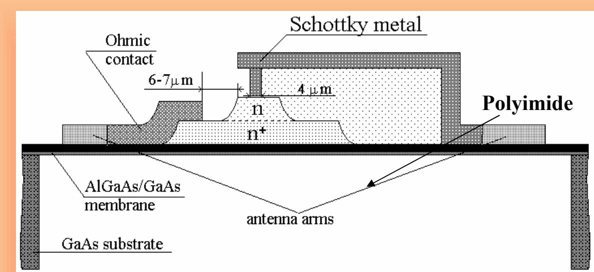
GaAs membrane supported coupled line filter for 45 GHz



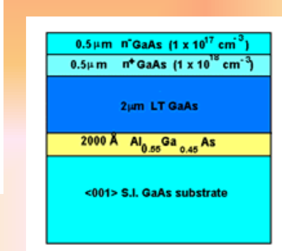
S parameter measurements for the new coupled line filter structure

Insertion losses lower than 0.8 dB

CONTENTS



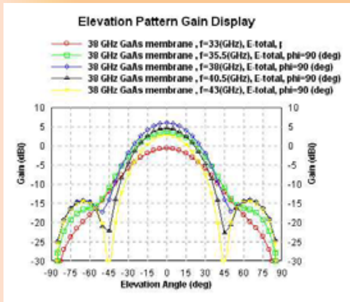
Cross section of the GaAs membrane supported receiver structure



GaAs Membrane Supported Receiver Heterostructure

An 8 masks process was developed 2001

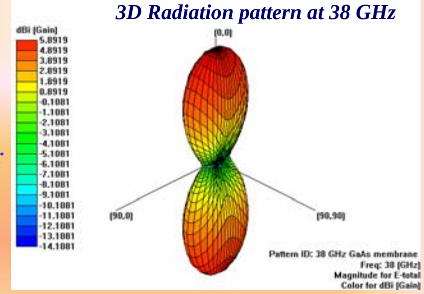
EM simulations for the membrane supported antenna



2D radiation pattern in the plane along the CPW feed line (E-plane)

- bidirectional and symmetric radiation pattern
- moderate gain of about 6 dBi in each direction
- the 3 dB loss caused by the bidirectional pattern is compensated by the flexibility offered by the design of the matching network using high impedance CPW lines as well as by the loss reduction obtained by micromachining

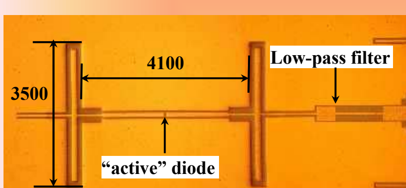
3D Radiation pattern at 38 GHz



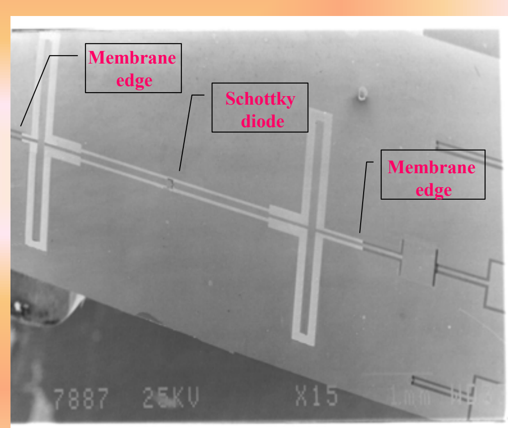
- simulations have shown that the antenna gain can be improved by another 2 dB by placing a reflector at the back of the receiver at an appropriate distance.
- it is possible to use the opposite lob to inject the local oscillator power in a mixer design with a quasi-optical configuration.

38GHz monolithic receiving module on GaAs membrane

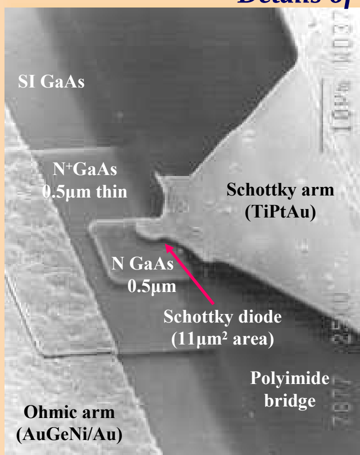
IMT -FORTH

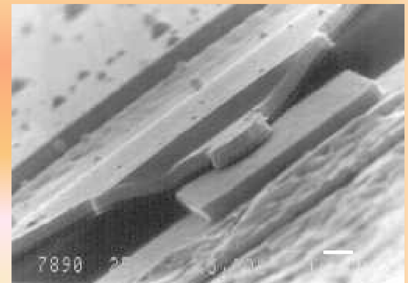


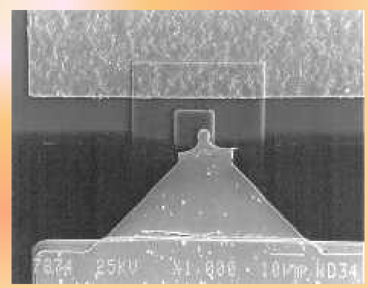
Membrane supported integrated 38 GHz GaAs micromachined receiving module (the antenna as well as the Schottky diode are supported on a 2.2µm thin GaAs membrane). The membrane is transparent in the white areas, which are unmetalized.



Details of the Schottky diode region

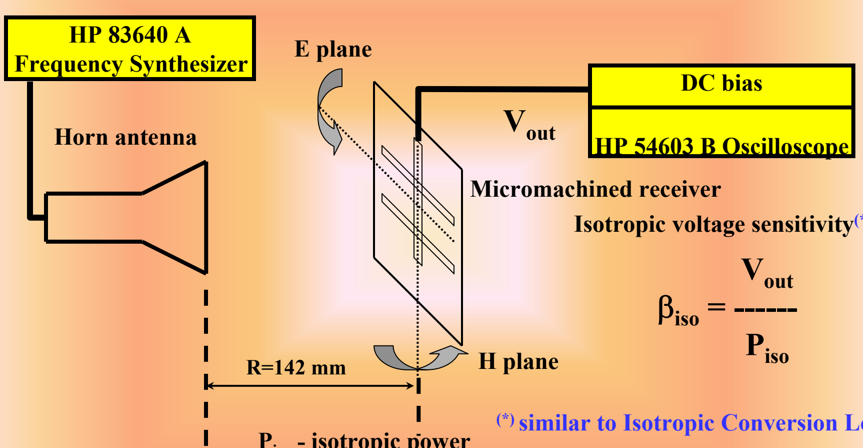






G Konstantinidis, M Lagadas, G Deligeorgis, A Müller, D Neculoiu, D Vasilache "GaAs membrane supported millimeter wave receiver structures" Journal Micromech. Microeng. 13 (2003) pp. 354-358

The experimental setup used for the microwave characterization

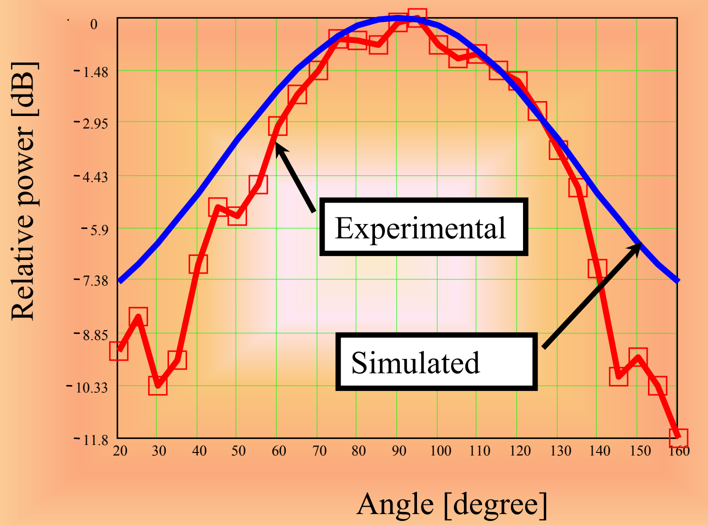


Isotropic voltage sensitivity(*):

$$\beta_{iso} = \frac{V_{out}}{P_{iso}}$$

(*) similar to Isotropic Conversion Loss, K.D.Stephan and T.Itoh, IEEE Trans. On MTT, No.1, 1984

Radiation pattern at 38 GHz – H plane



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Isotropic voltage sensitivity vs. input isotropic power at 38 GHz

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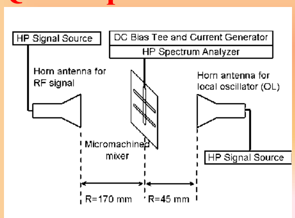
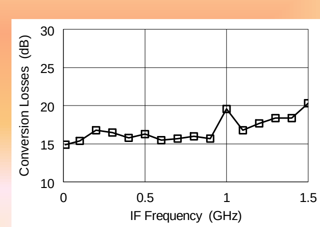
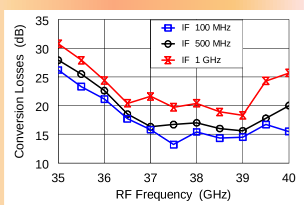
Quasi-optical mixer using a GaAs monolithic structure



The experimental setup used for the characterization of the micromachined quasi-optical mixer



The isotropic conversion losses of upper sideband versus IF frequency

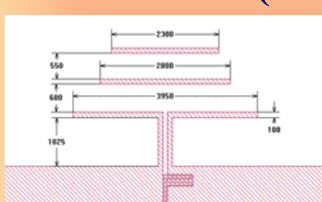


The isotropic conversion losses of upper sideband versus RF frequency

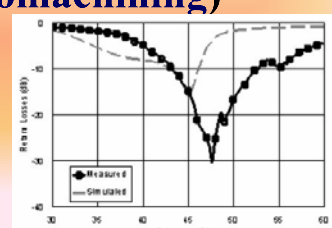
The second lob of the membrane supported slot antenna can be useful !

D Neculoiu, G Bartolucci, G Konstantinidis, R Marcelli, I Petrini, M Dragoman, D Vasilache and A Muller "A Micromachined 38 GHz Schottky-Diode Uniplanar Monolithic Integrated Quasi-Optical Mixer" ***2004 IEEE Radio Frequency Integrated Circuits (RFIC) Symposium, Forth Worth, TX-June 6-8, 2004 pp. 531-534***

Yagi-Uda Antennae
45 GHz (GaAs micromachining)



Optimized layout for Yagi-Uda antenna

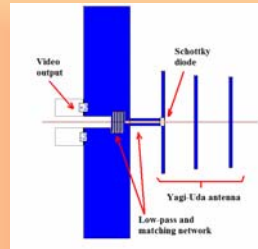


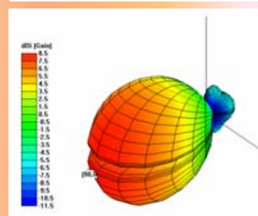
Measured and simulated return losses

Fabricated Yagi-Uda antenna

A. Pantazis, D. Neculoiu, Z. Hazoupulos, D. Vasilache, M. Lagas, M. Dragoman, C. Buiculescu, I. Petrini, A. A. Muller, G. Konstantinidis, A. Muller "Millimeter wave passive circuits elements based on GaAs micromachining", Journal of Micromech. Microeng., vol.15, pp.S-53-S59, 2005

EM model of the membrane supported receiver module

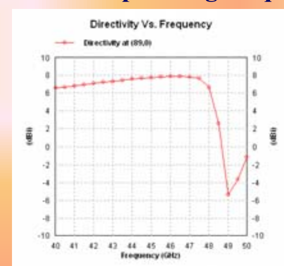




3D radiation pattern at 45 GHz

Optimization goals:

- **diode matching (the bias dependent small signal diode equivalent is used)**
- **maximum antenna gain at 45 GHz central operating frequency**



Antenna directivity vs. frequency

Technological process

The MBE structure

- ❑ Conventional and low temperature III-V MBE growth was used to fabricate the GaAs/AlGaAs/GaAs heterostructure
- ❑ Semi-insulating GaAs wafers ($\rho = 10^7\ \Omega$cm), with a thickness of 460µm, were used as substrate
- ❑ $Al_xGa_{1-x}As$ (with x.0.5) with a thickness of 2000Å was used as etch stop layer
- ❑ LT GaAs was used as membrane layer
- ❑ An 8 masks process was developed

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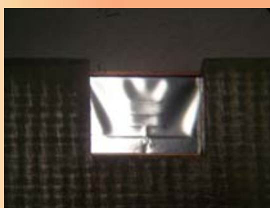
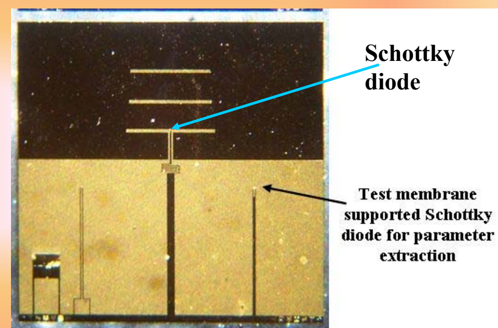
The final structure





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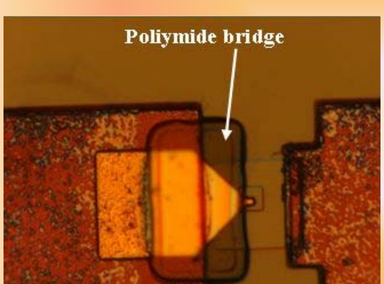
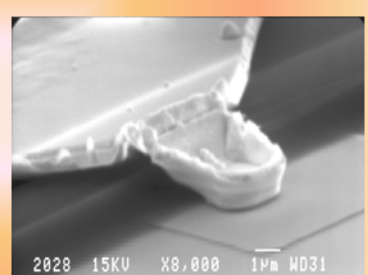
Details of the Schottky diode region





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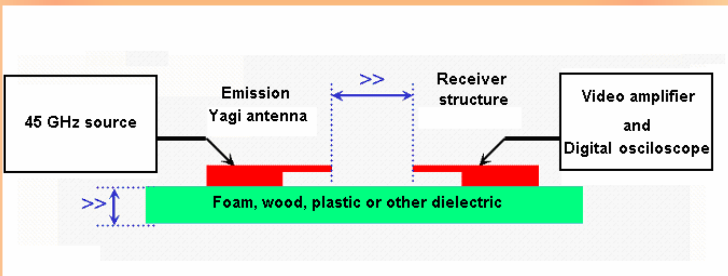
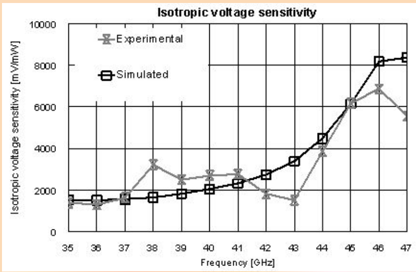
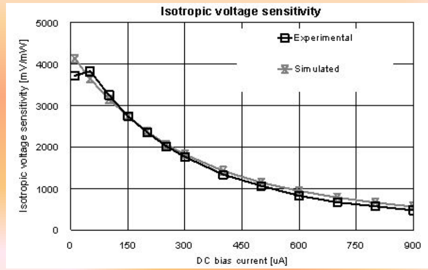
Yagi-Uda antenna receiver



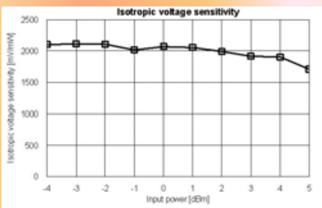
The experimental setup used for the "on wafer" microwave characterization



Isotropic voltage sensitivity vs frequency



Isotropic voltage sensitivity vs DC bias current



Isotropic voltage sensitivity vs input power

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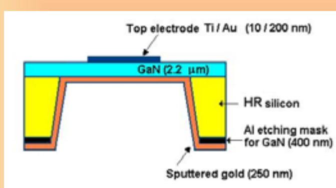
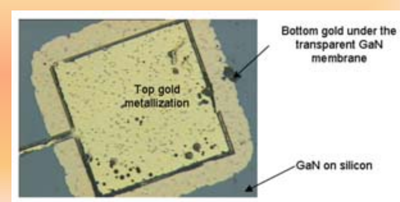
- Introduction
- Silicon micromachined membrane supported circuits
  - Membrane supported filters
  - Membrane supported antennae
  - Hybrid integrated receiver structures with folded slot antennae
- GaAs membrane supported circuots for millimeter wave communications
  - Technology
  - GaAs membrane supported filters and Yagi-Uda antennae
  - Monolithic integrated millimeter wave receiver structures (with folded slot and Yagi-Uda antennae)
- Developments in progress
- Conclusions

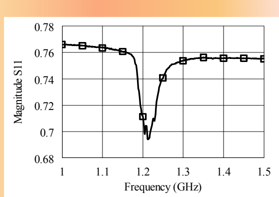
GaN membrane supported FBAR structures



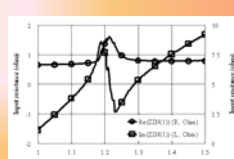
Cross section of the GaN membrane supported FBAR test structure



Top optical photo of the active area of the experimental F-BAR structure.



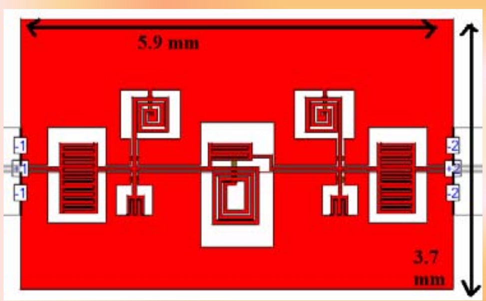
Return losses vs frequency for the GaN membrane supported FBAR structure



Real (right vertical axis) and imaginary part (left vertical axis) of the impedance for the measured GaN F-BAR test structure

WLAN 5200 filter layout

(on SiO_2/Si_3N_4 membrane)



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Conclusions

- Dielectric or h.r. semiconductor membranes represent an important development for manufacturing high performance passive circuit elements in the millimeter wave range.
- It is possible to integrate (hybrid or monolithic) passive membrane supported circuit elements with active components in complex circuits (SiC)
- The advantage of these technology will become evident in the near future when the communication systems will extend in the millimeter and sub-millimeter frequency range

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(MEMSWAVE)
Project No.977131
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IMT-Bucharest (Project coordinator)

Partners:

FORTH Heraklion
ITC-IRST Trento
Uppsala University
Tor Vergata Univ. Rome
CNR-M^{2}T Rome
HAS-MFA Budapest
ISP Kiev
Microsensor Kiev Ltd.

TARGETS

- **Thin dielectric membranes on high resistivity silicon substrate;**
- **GaAs membranes manufacturing;**
- **Micromachined passive circuit elements on silicon and GaAs substrate;**
- **Micromachined millimetre wave band pass filters and antennas;**
- **Receiver modules for 38GHz and 77GHz based on micromachining technology;**
- **Transmitter module for 38GHz.**

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Coordinator – LAAS CNRS Toulouse

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