

Obsah

Využitie mikrosystémovej techniky pri výrobe MEMS a mikrosenzorov

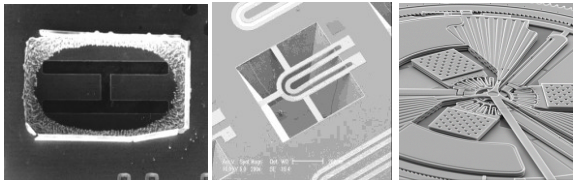
- Čo sú to MEMS?
- Ako ich vyrobiť?
- Ako ich merať?
- MEMS tlakový senzor
- Príklady z EIÚ SAV

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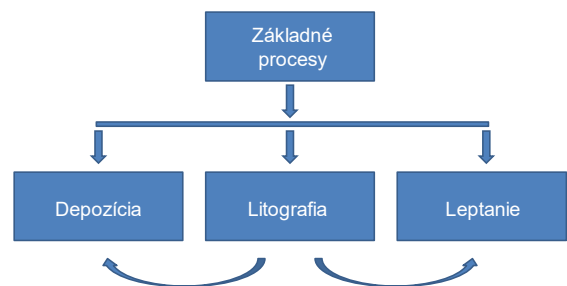
MEMS

- Mikro-Elektro-Mechanické-Systémy

Rozmery 1 μ m - 1mm



Technológia

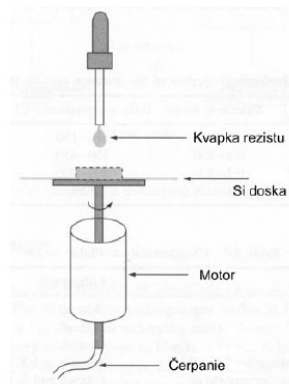


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Stavíme ← Plánujeme → Vítame

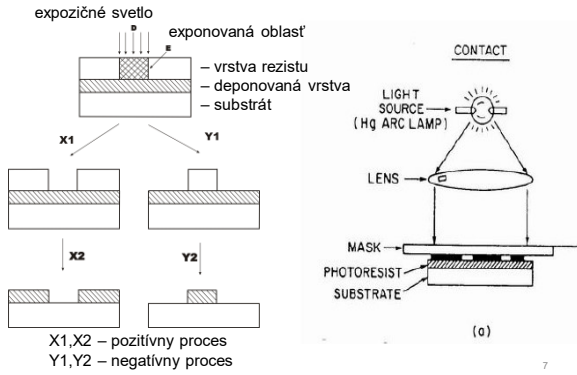


Nanášanie rezistu



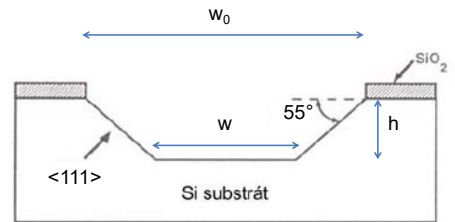
- A – odmastenie vzorky
- B – nanosenie rezistu s presnou hrúbkou
- C – vypekánie

Fotolitografia



1000 (US norma), 1000 častic (< 0.5 μm) /stopa³ (ISO 5),
vlhkosť: 40 % ± 1 %, teplota: 22 °C ± 1 °C

Mokrú leptanie



$$w = w_0 - 2h \coth(55^\circ) \quad \text{alebo} \quad w = w_0 - 1,4h$$

$$100 = 520 - 1,4 \cdot 300$$

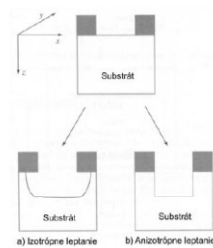
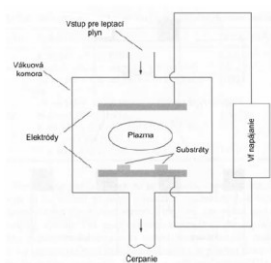


SÜSS MJB 21 Mask Aligner

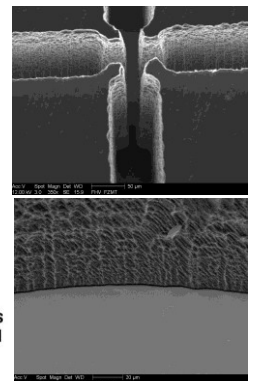
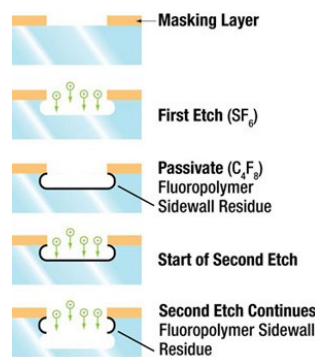


SÜSS MJB 3 Mask Aligner

Suché leptanie

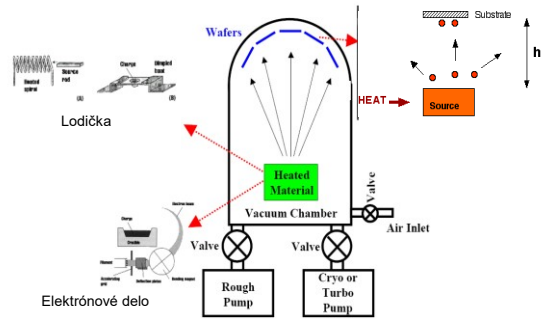


Bosch process

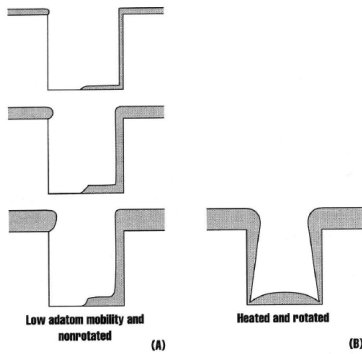




Naparovanie



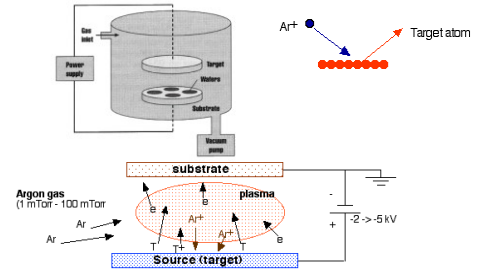
Naparovanie



Naprašovanie

Výhody: lepšie pokrytie, menšie radiačné poškodenie, nanášanie zliatin

Nevýhody: poškodenie spôsobené plazmou

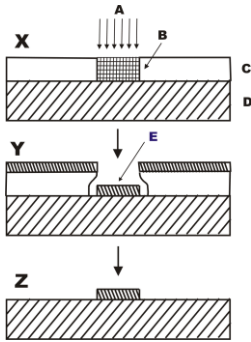


Naparovanie elektrónovým zväzkom



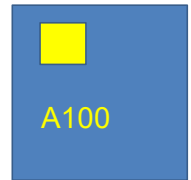
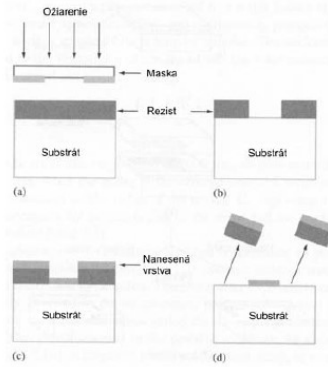
Naprašovanie

Technika „lift-off“



- A - expozičné svetlo
- B - exponovaná oblasť
- C - fotorezist
- D - substrát
- E - deponovaná vrstva

Technika „lift-off“

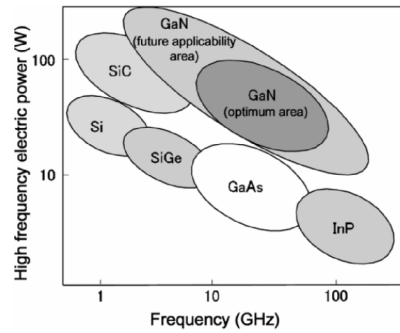


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Porovnanie materiálov

material	bandgap (eV)	relative dielectric constant	effective electron mass	electron mobility ($\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$)	break-down field (10^6 V cm^{-1})	saturation electron velocity	thermal conductivity ($\text{W cm}^{-1} \text{K}^{-1}$)	Transition n type ($10^{17} \text{ V cm}^{-1}$)
InN	0.6 ~ 0.7	15.0	0.04	4,000	2.0	4.2	0.8	direct
GaN	3.4	9.5	0.22	1,200	3.0	2.5	2.1	direct
AlN	6.2	8.5	0.29	-	-	2.0	2.9	direct
Si	1.1	11.8	0.19	1,500	0.3	1.0	1.5	indirect
GaAs	1.4	12.8	0.067	8,500	0.4	2.0	0.5	direct
4H-SiC	3.3	10.0	0.3	1,000	3.0	2.0	4.9	indirect
diamond	5.5	5.5	0.2	1,800	4.0	2.5	20.9	indirect

Porovnanie materiálov



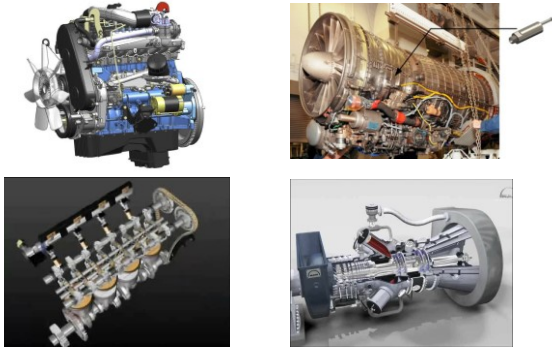
Tlakové MEMS senzory na EIÚ SAV



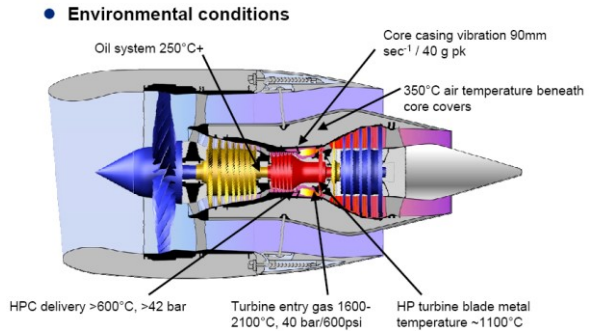
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Aplikácie tlakového senzora

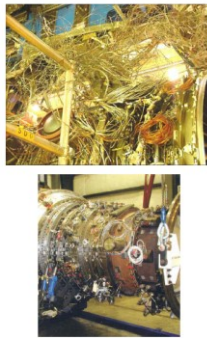


Three shaft civil turbofan



Wireless Sensors - Motivation

- **Current state of the art**
 - 3000+ parameters measured on development engine
 - Miles of sensor wiring
 - Cables expensive, present risk of failure
 - Cables tie engine modules together – difficult to dismantle engine in case of problem
 - ⇒ Build and test bed change can be long and expensive
- **Wireless sensors enabling technology for cost savings**

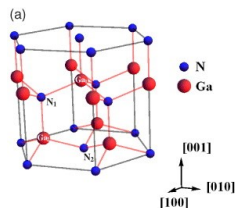
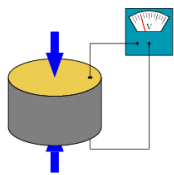


C-HEMT senzor

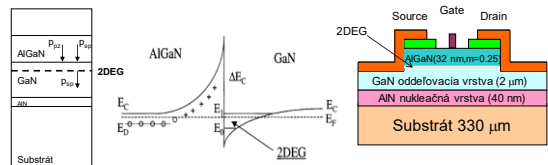
Princíp - piezoelektrický jav

Nehostinné prostredia

⇒ odolné materiály (AlN, GaN, AlGaN)

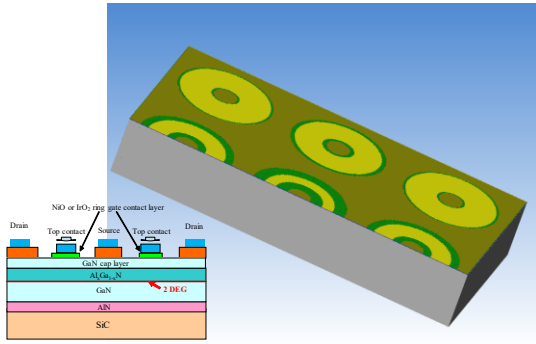


C-HEMT

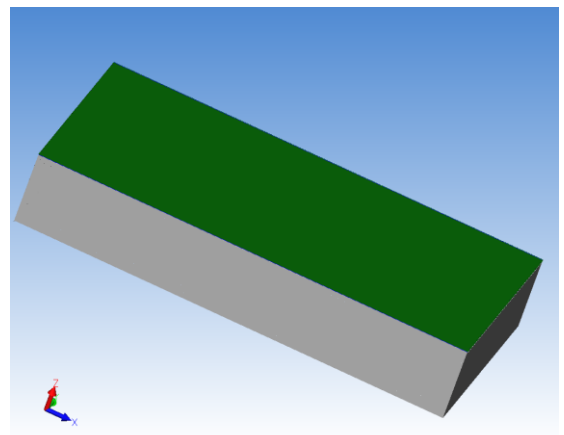
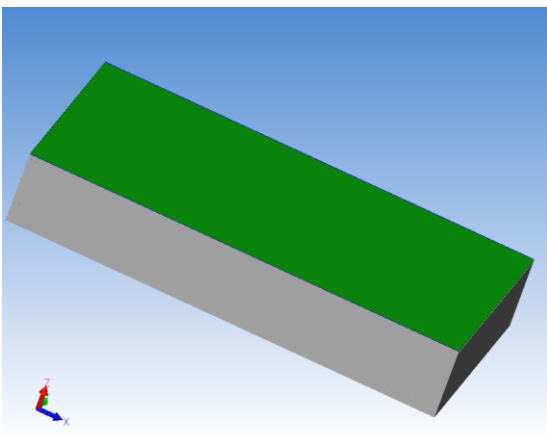
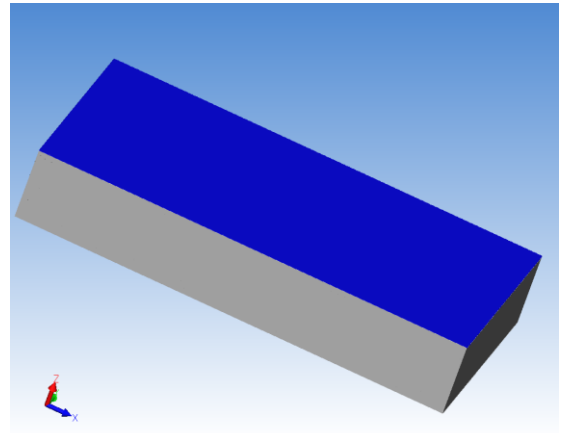
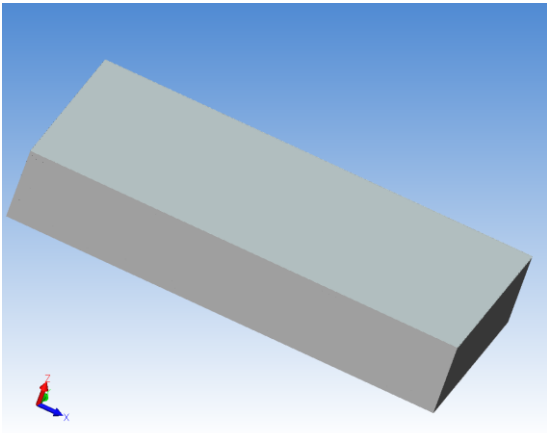
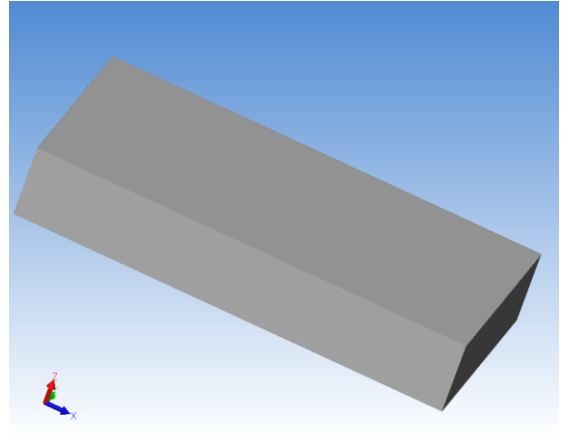


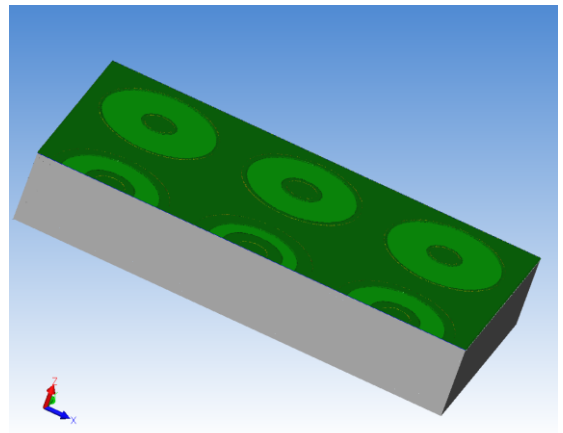
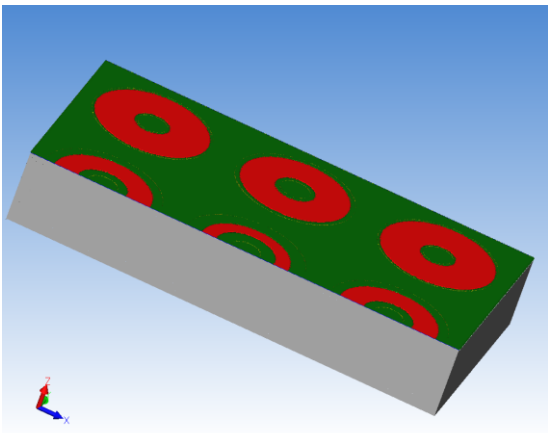
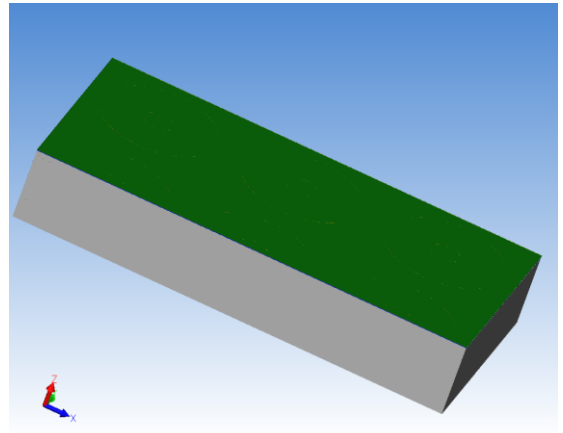
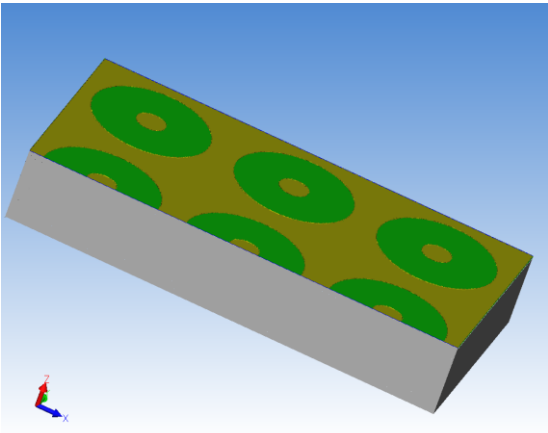
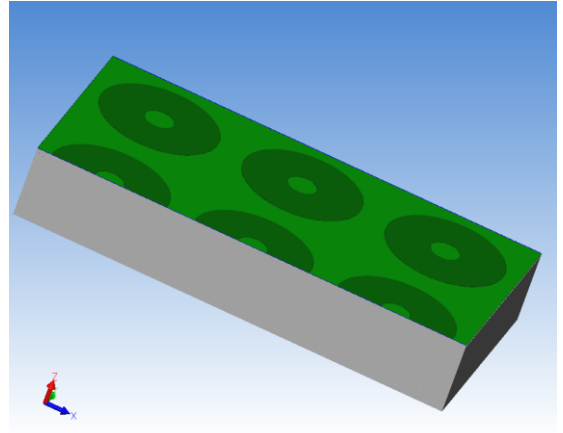
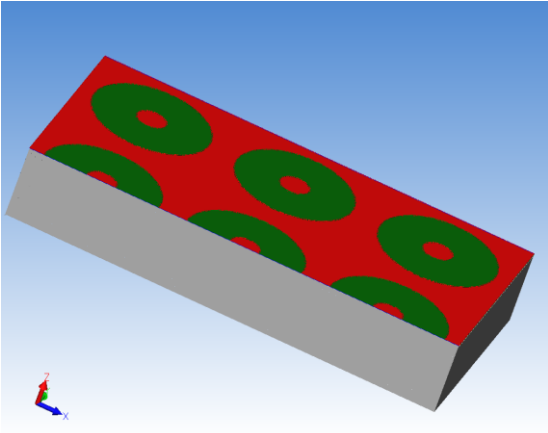
- Spontánna a piezoelektrická polarizácia v napnutých vrstvách AlGaN a GaN
- Elektróny zachytené vo forme 2DEG na rozhraní AlGaN/GaN
- Zmena polarizácie v dôsledku pôsobenia externých síl
- Využitie pre konštrukciu tlakových senzorov

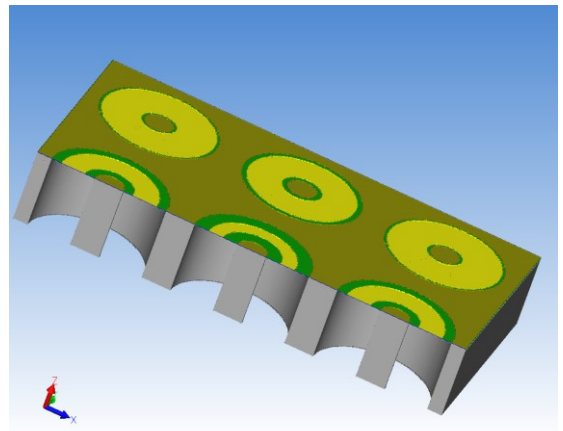
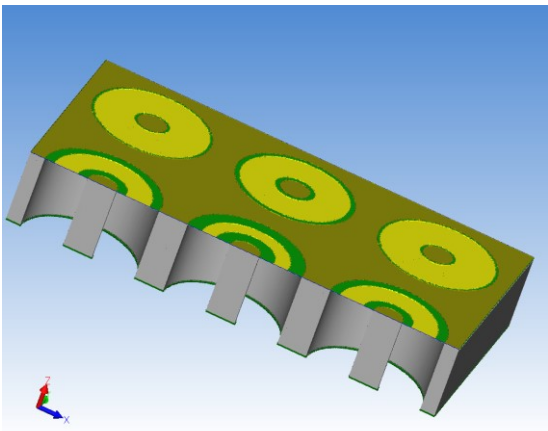
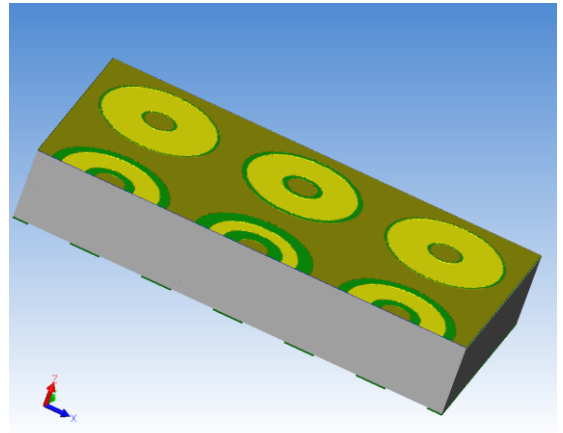
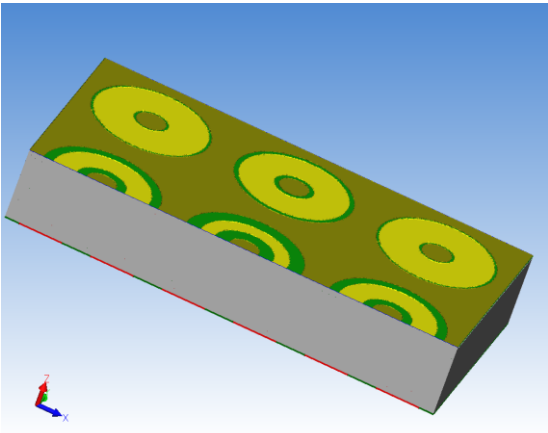
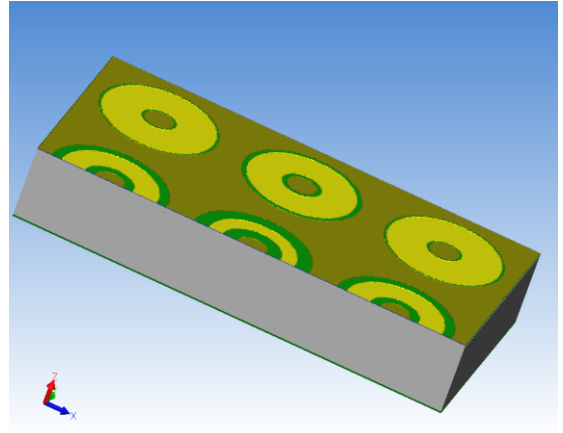
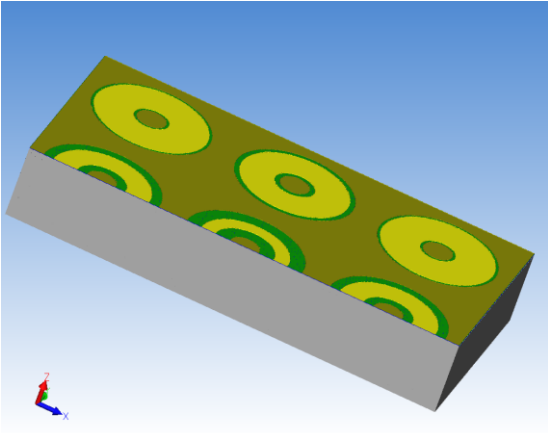
C-HEMT

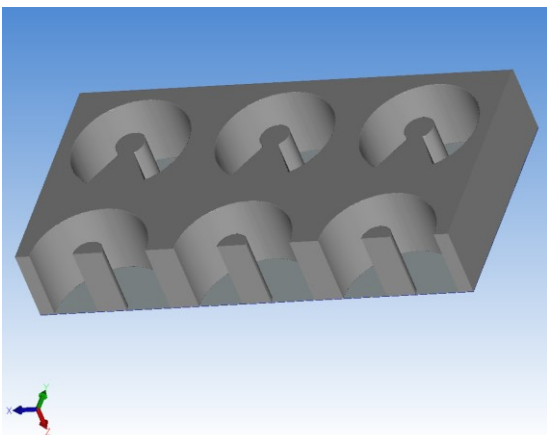
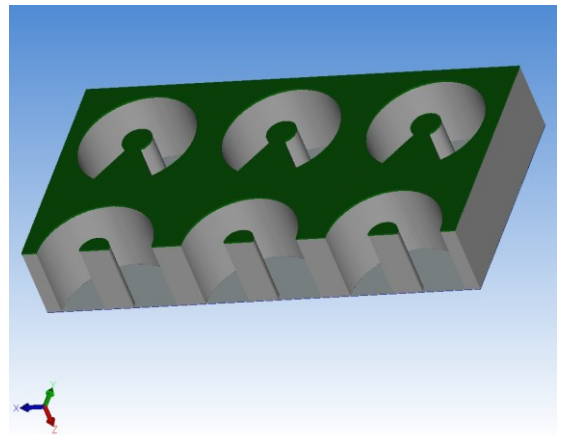
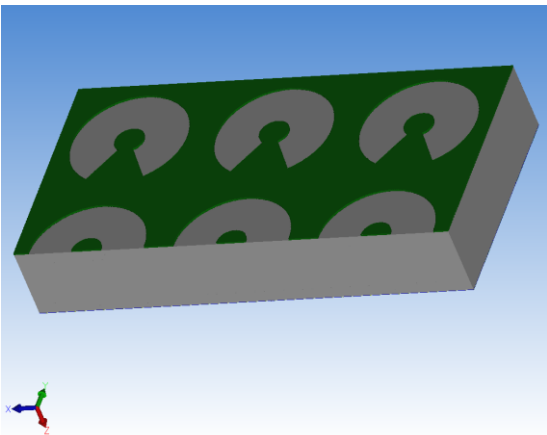
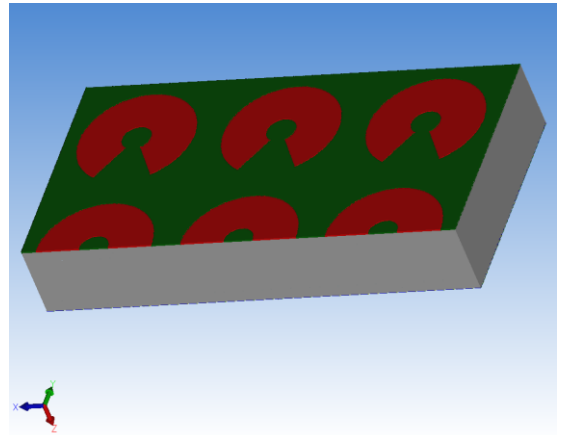
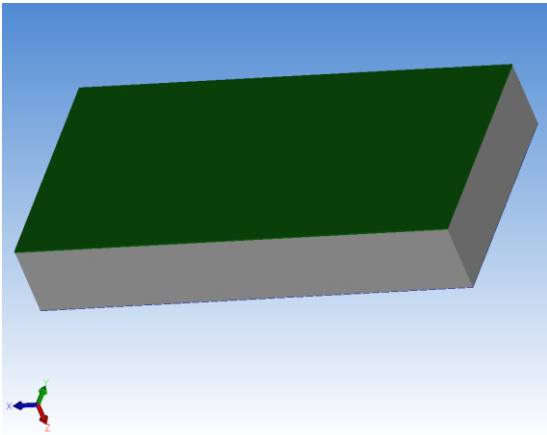


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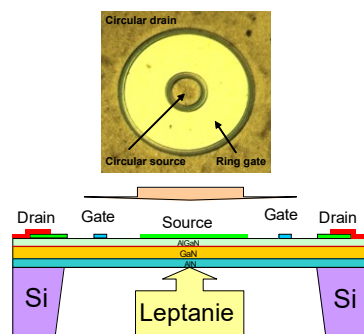




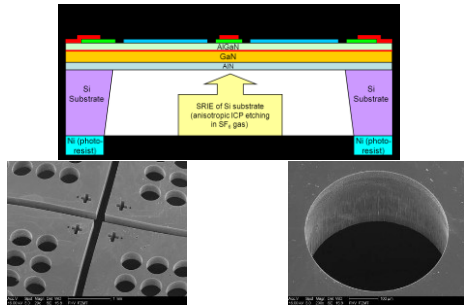




C-HEMT



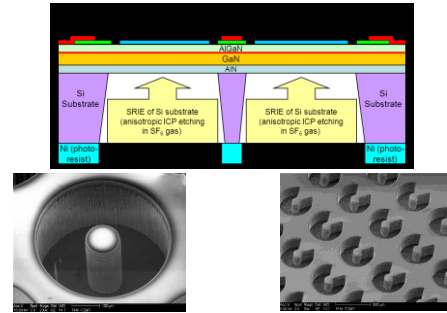
C-HEMT



Circular membranes defined by a deep back-side etching of Si substrate

Circular membrane defined by a deep back-side etching of Si substrate

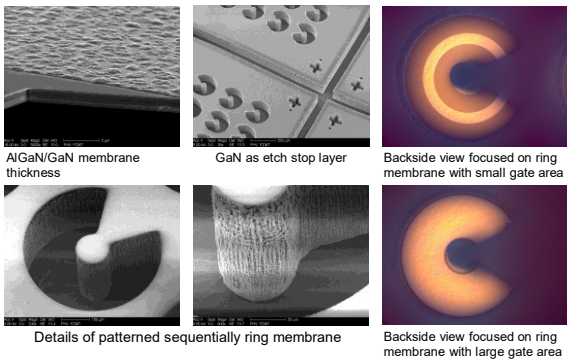
C-HEMT



Circular ring membrane defined by a deep back-side etching of Si substrate

A sequential circular ring membrane defined by a deep back-side etching of Si substrate

C-HEMT



AlGaIn/GaN membrane thickness

GaN as etch stop layer

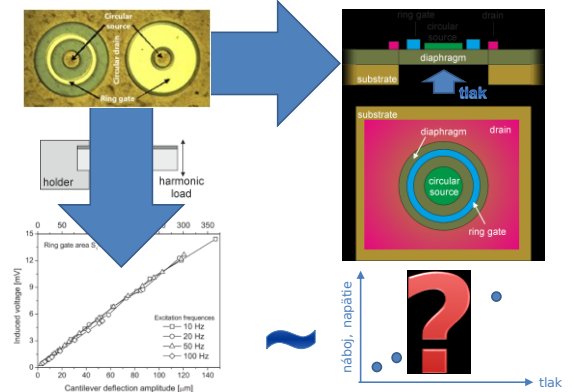
Backside view focused on ring membrane with small gate area

Details of patterned sequentially ring membrane

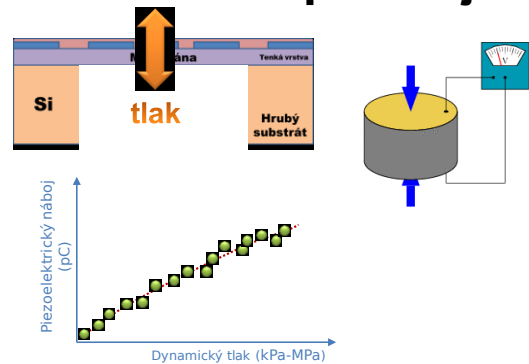
Backside view focused on ring membrane with large gate area

Návrh senzora

<BACK

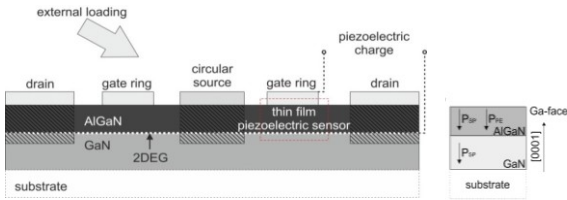


Membrána + piezoeel. jav



Tlakové MEMS senzory

Princíp činnosti



Layers:

AlGaN 20 nm
 GaN 4.2 μm
 Si sub 350 μm

Ohmic:

Nb / Ti / Al / Ni / Au
 20 / 20 / 120 / 40 / 70 nm

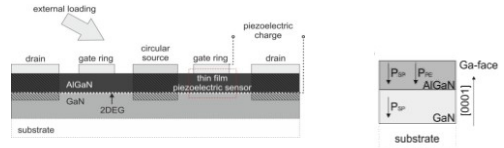
Schottky:

Ni / Au
 40 / 120 nm

Top:

Ti / Au
 30 / 120 nm

Princíp činnosti

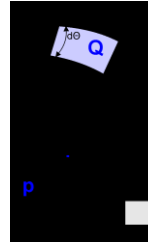


$$Q = \oint_{SV} DndA \quad D = eS + \epsilon E$$

$$Q = \int D_3 dA = \int_0^{2\pi} \int_{R_1}^{R_2} \epsilon_{31} S_R r dr d\theta$$

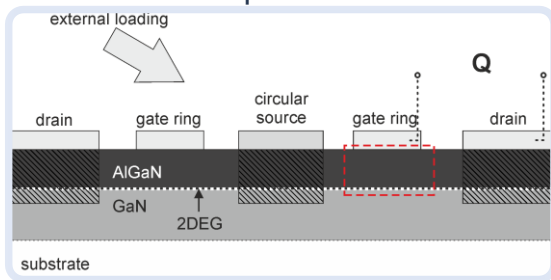
$$-\frac{pR_C}{2t} = \sigma_0 + \sigma_p \quad R_C = \frac{d^2 + 4w^2}{8w}$$

$$Q = \frac{\pi(R_1^2 - R_2^2)e_{31}}{Y} \left(\frac{R_C}{2t} p - \sigma_0 \right)$$



<BACK

Princíp činnosti

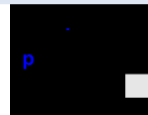
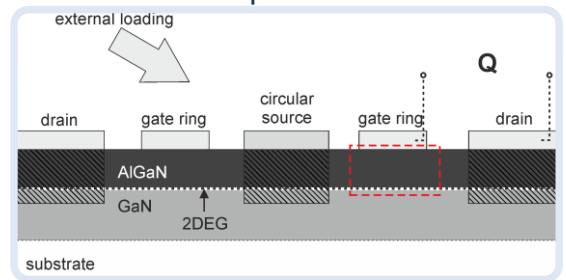


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<BACK

Princíp činnosti

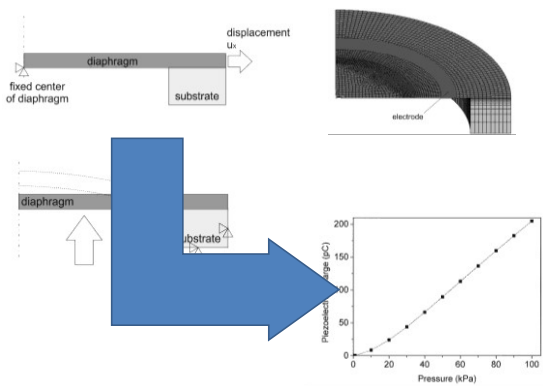


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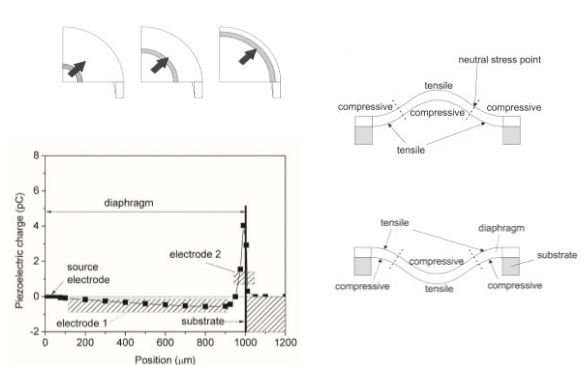
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FEM model



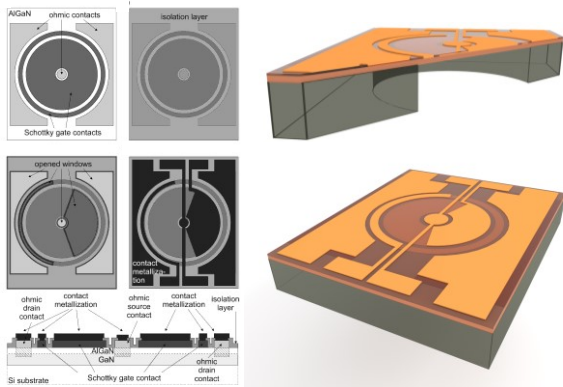
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FEM model

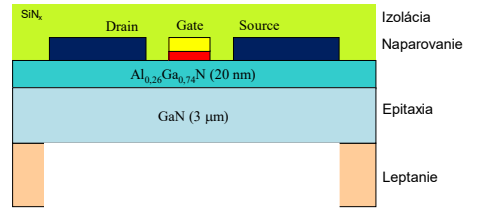


Layout

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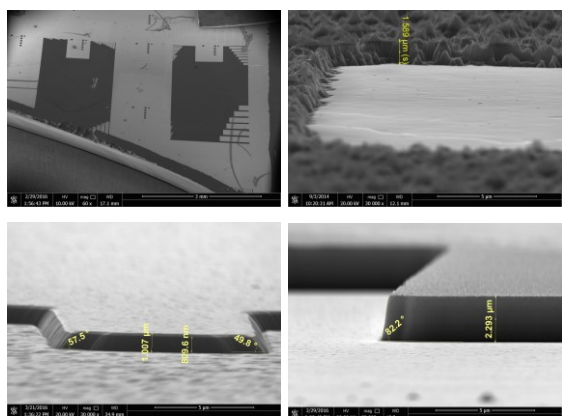
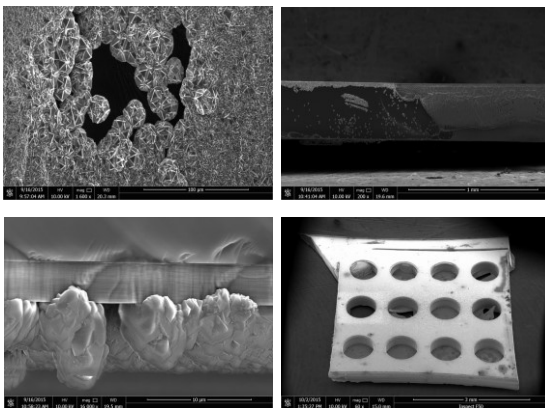
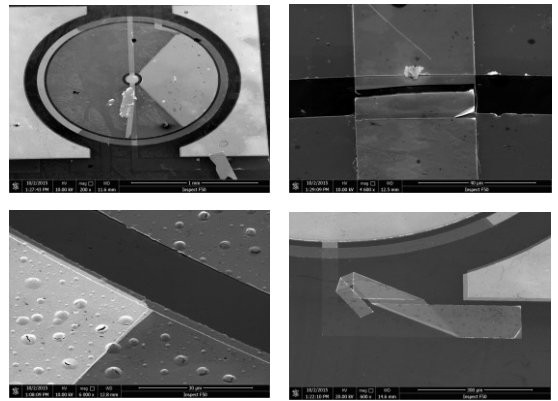
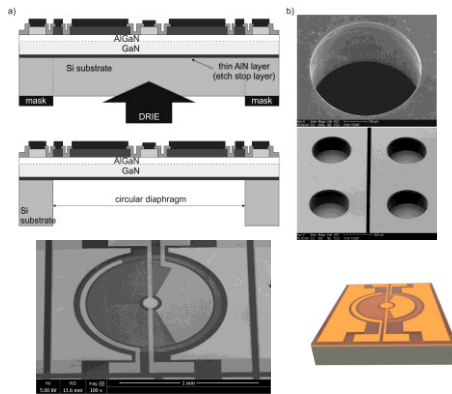
Procesná technológia



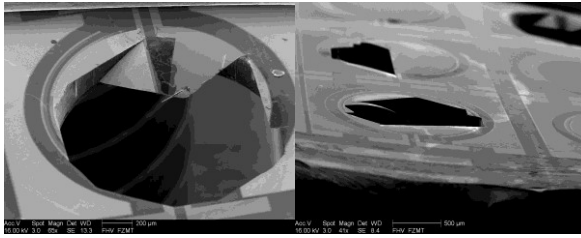
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Súčiastka

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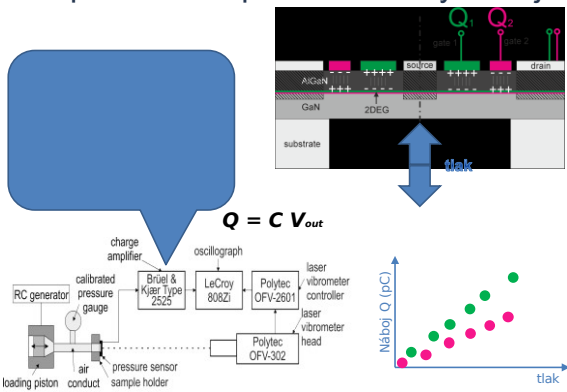
Praskanie membrán



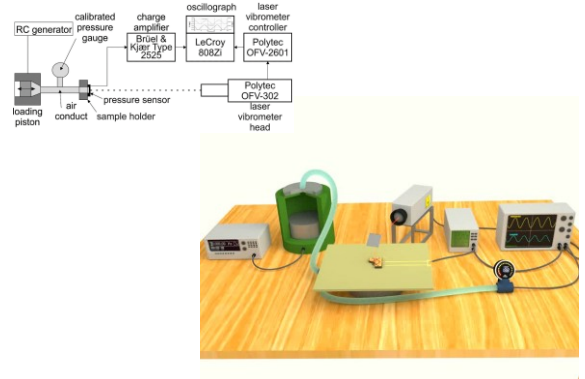
Praskanie membrán



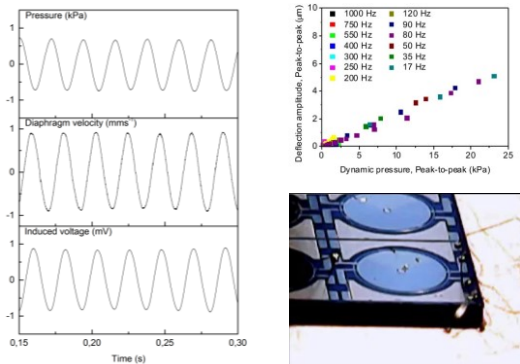
Experiment ⇒ piezoelektrický náboj ^{<BACK}



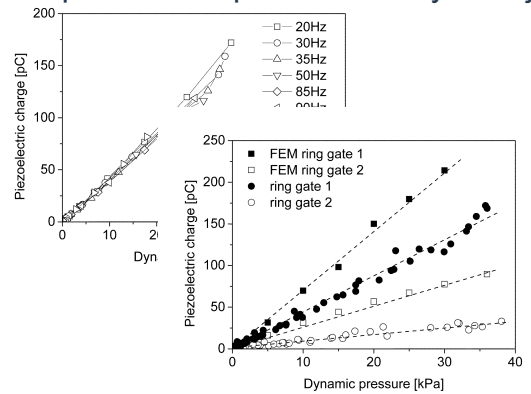
Experiment ⇒ piezoelektrický náboj



Experiment ⇒ piezoelektrický náboj ^{<BACK}

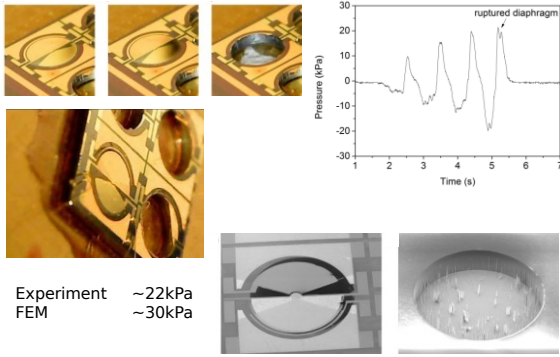


Experiment ⇒ piezoelektrický náboj



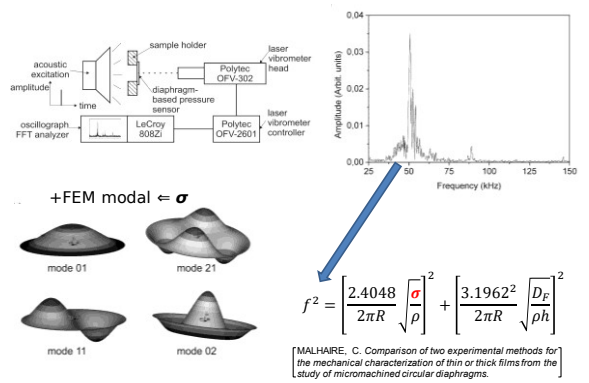
Experiment ⇒ kritický tlak

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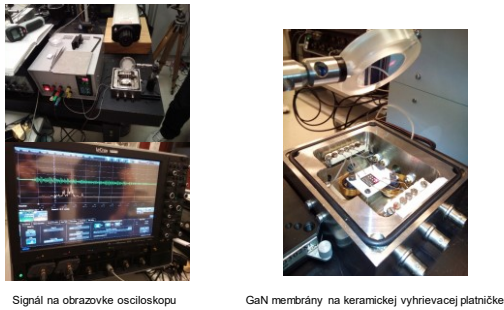


Experiment ⇒ σ (rezonančná metóda)

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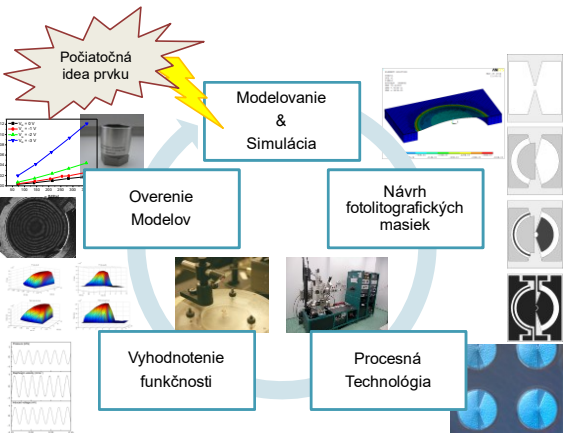
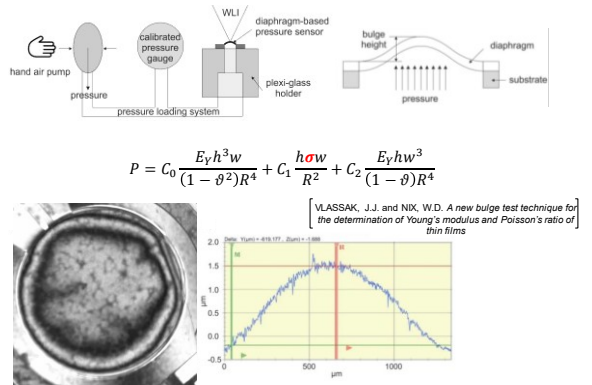
Experiment ⇒ σ (rezonančná metóda)



81

Experiment ⇒ σ (vychyľovacia metóda)

<BACK



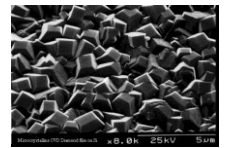
Ďalšie príklady

84

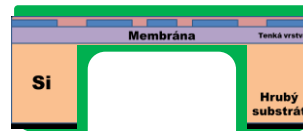
Aplikácia diamantových vrstiev (NCD/MCD)

AlGaN/GaN + DIAMANT

Unikátne vlastnosti diamantu
 vysoká pevnosť
 vysoká tepelná vodivosť
 nízka teplotná rozťažnosť



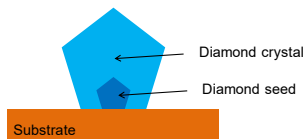
diamant



CVD of diamond films

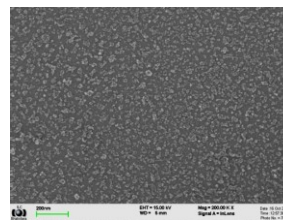
Nucleation (seeding)

Diamond growth



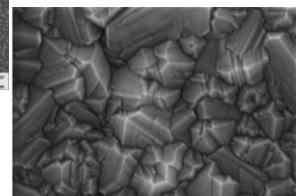
CVD of diamond films

SEM observation:

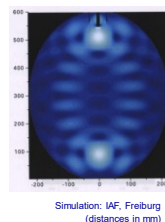


Nucleated substrate

Diamond film grown by CVD method



Ellipsoidal cavity resonator Aixtron P6



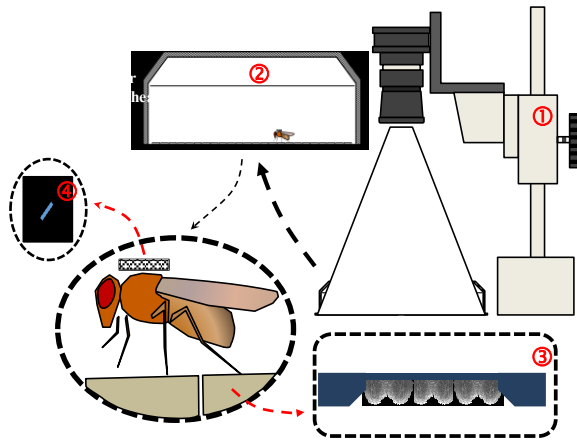
Substrate holder

Quartz bell jar

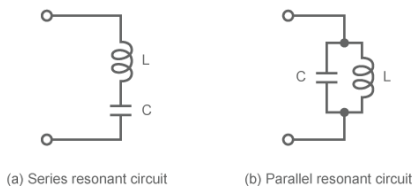


Mikrožariče

Design

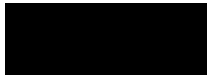


LC resonant circuit

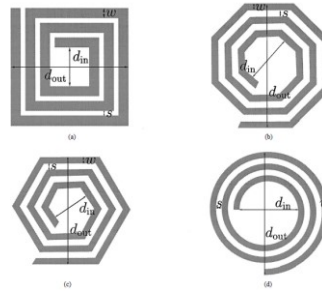


(a) Series resonant circuit

(b) Parallel resonant circuit



On-chip inductor realization

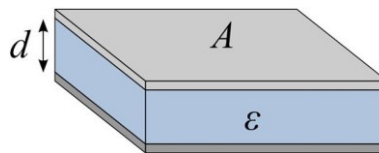


$$L = \left[\frac{\mu_0 N^2 D_{AVG} C_1}{2} \right] \left[\ln \left(\frac{C_2}{\rho} \right) + C_3 \rho + C_4 \rho^2 \right]$$

where N is the number of turns, μ_0 is the vacuum permeability ($4\pi \times 10^{-7}$), ρ is the fill ratio, D_{AVG} is the average diameter, and C_1-C_4 are the factors related to the layout [6].

S.S. Mohan, et al., IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 34, NO. 10, OCTOBER 1999

LC resonant circuit



TESLA INSTITUTE Single layer Planar spiral coil inductor calculator

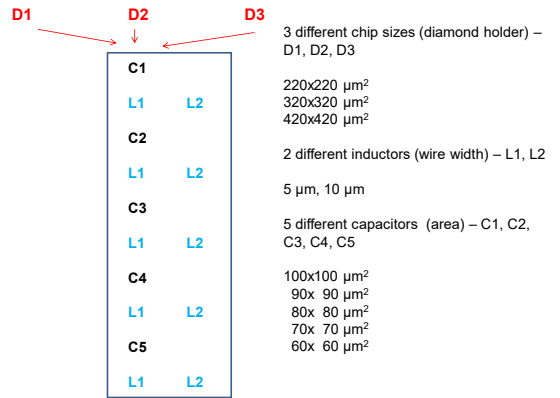
	Square	Hexagonal	Octagonal	Circular
Modified Wheeler	43.613	31.623	32.29	32.762
Current Sheet	43.597	34.09	34.266	33.081
Modified FB	43.118	34.809	32.649	32.446

References
 1- S. S. Mohan, M. M. Hachem, S.P. Boyd and T.H. Lee
 2- Simple Accurate Expressions for Planar Spiral Inductances IEEE Journal of Solid State Circuits, Oct. 1999, pp. 1419-24.
 For multilayer spiral coils see the file: "A.comCalculatorForDesigningMultilayerPlanarSpiralInductors"

High-K dielectrics

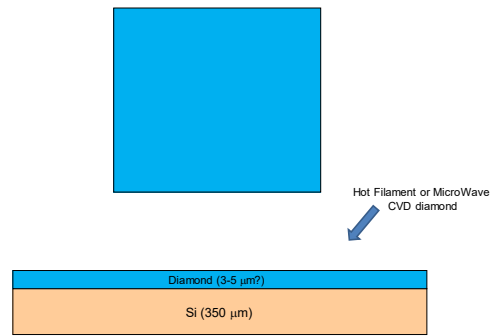
	K	Gap (eV)	CB offset (eV)
Si		1.1	
SiO ₂	3.9	9	3.2
Si ₃ N ₄	7	5.3	2.4
Al ₂ O ₃	9	8.8	2.8 (not ALD)
Ta ₂ O ₅	22	4.4	0.35
TiO ₂	80	3.5	0
SrTiO ₃	2000	3.2	0
ZrO ₂	25	5.8	1.5
HfO ₂	25	5.8	1.4
HfSiO ₄	11	6.5	1.8
La ₂ O ₃	30	6	2.3
Y ₂ O ₃	15	6	2.3
a-LaAlO ₃	30	5.6	1.8

J. Robertson, Eur. Phys. J. Appl. Phys. 28, 265–291 (2004)

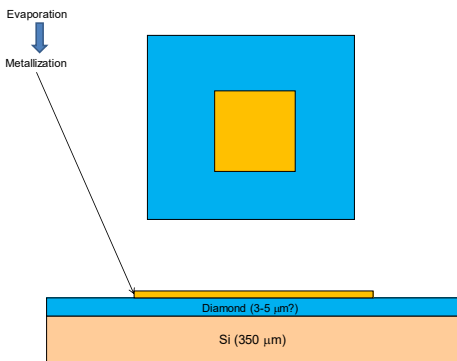


Processing technology

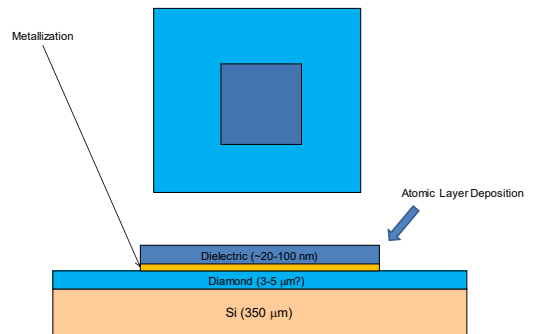
LC Heater

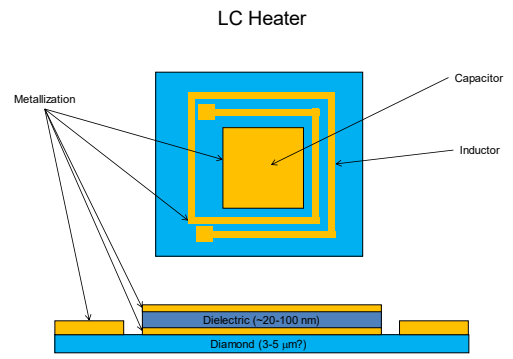
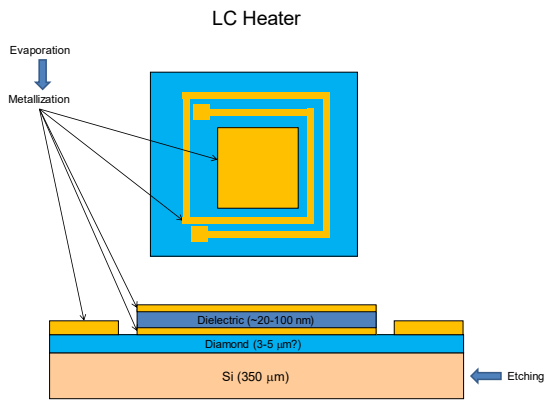


LC Heater

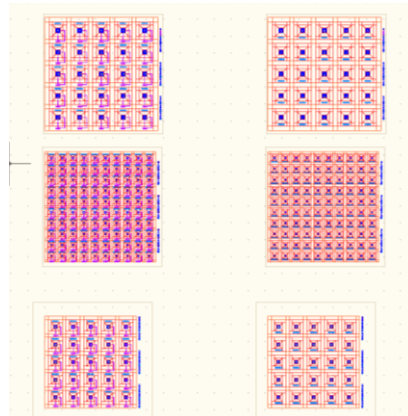
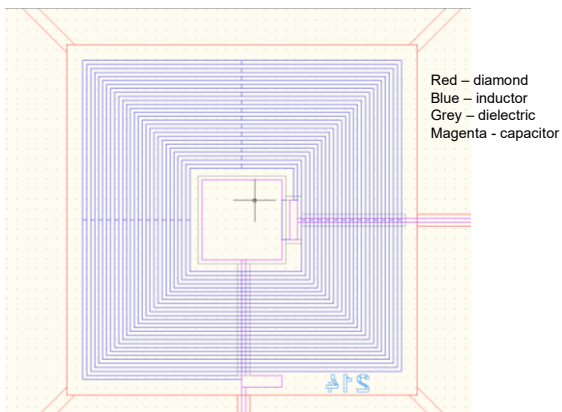
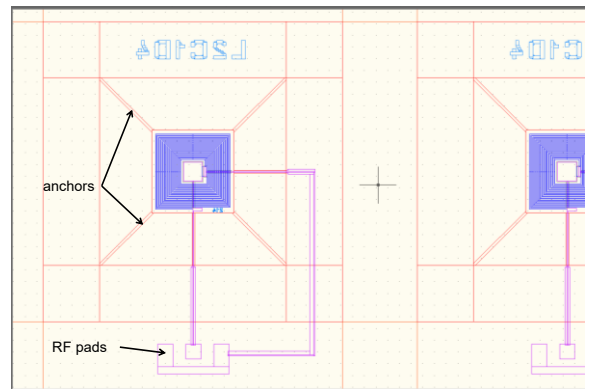


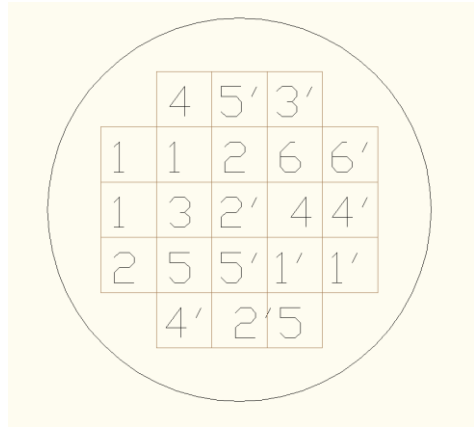
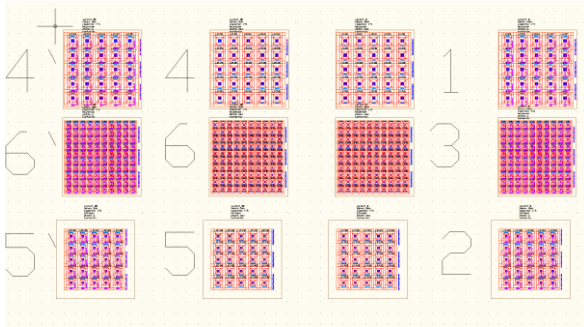
LC Heater





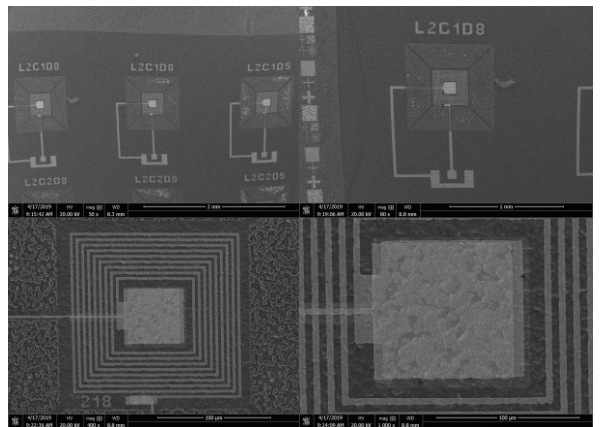
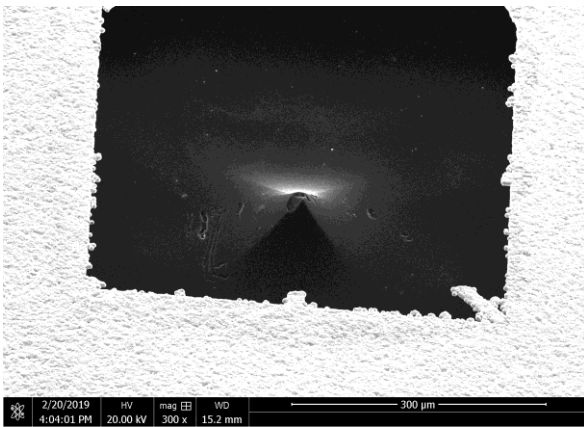
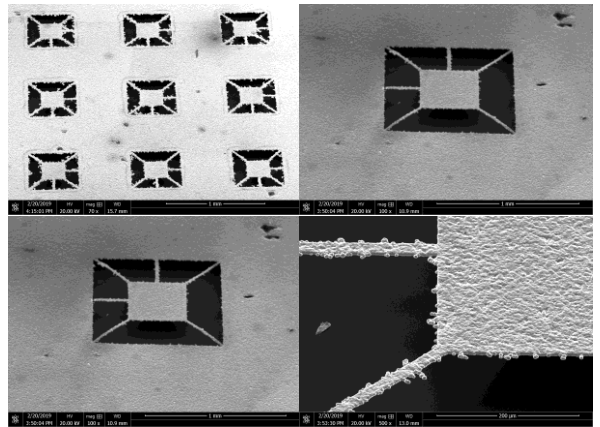
AutoCAD Layout

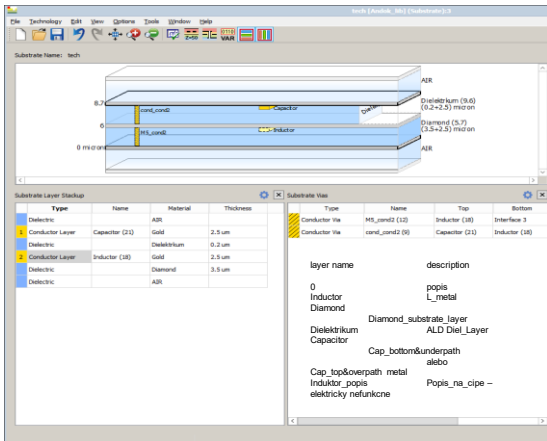
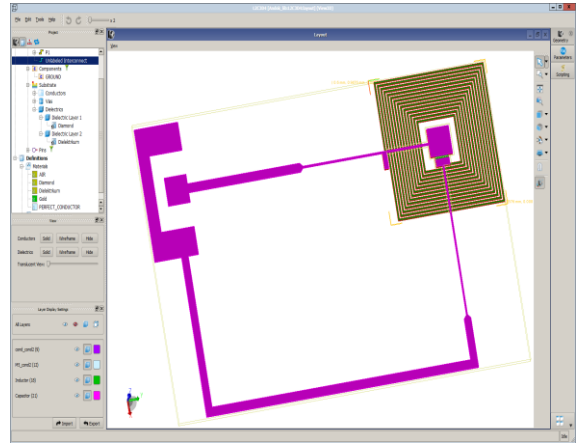
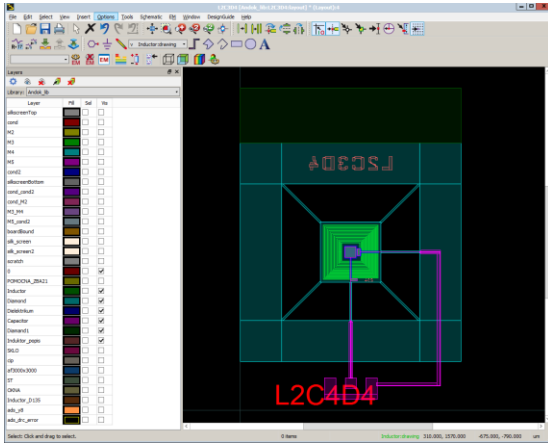




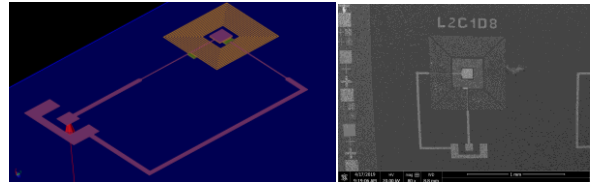
Technology

- Selective area diamond deposition on Si substrates;
- Evaporation of Ti(20nm)/Au(80nm) – Inductor and first electrode of Capacitor
- Atomic Layer Deposition (ALD) of dielectric layer
- Evaporation of Ti(20nm)/Au(80nm) – second electrode of Capacitor
- Wet etching of Si



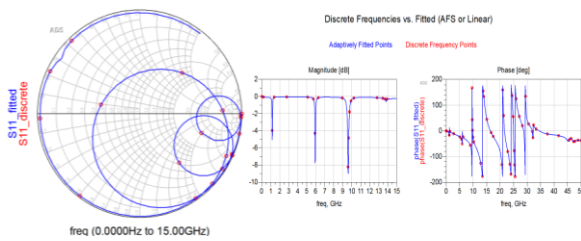


μ-heater RF simulation



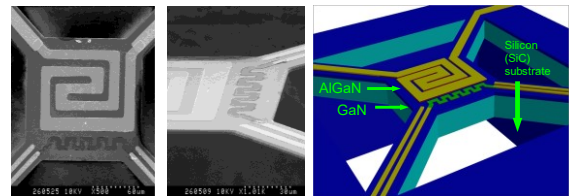
Schematic view of the designed planar square LC resonant circuit (chip area 300×300μm²) with expanded contacts for the rf characterization (left) and the SEM micrograph of the fabricated real device before diamond membrane release (right).

μ-heater RF simulation



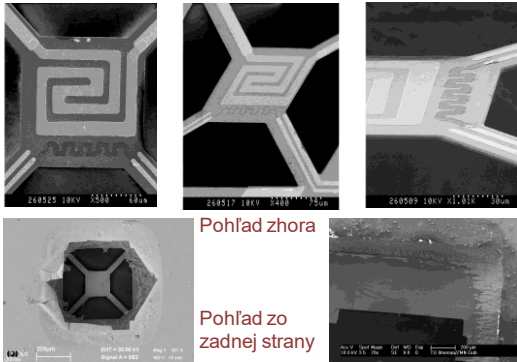
Simulated frequency response of proposed resonant circuit: Reflection coefficient in Smith diagram (left); reflection coefficient magnitude and phase (right).

Mikrožarič pre vodivostný typ plynového senzora



- Tepelná izolácia dosiahnutá pomocou AlGaIn/GaN membránovej štruktúry (využitie nižšej tepelnej vodivosti okolia)
- navrhnutá topológia s AlGaIn/GaN HEMT ako žiarivcom a Schottkyho diódou vo funkcii teplotného senzora

Mikrožiarč a senzor



Pohľad zhora

Pohľad zo zadnej strany

MEMS senzory mikrovlnného výkonu

[18] T. Lohmeyer et al.: 14th MicroMechatronics Europe Workshop, 2006, (2006)
 [19] T. Lohmeyer et al.: Sensors and Actuators A 123-124 (2005)
 (NATO SIP project, VEGA projekt)

Po prvý krát prijatý koncept návrhu tepelného prevodníka na báze polyimidom fixovanej štruktúry ostrovčeka, HEMT žiaríča a TS (Spolupráca s ÚI SAV, Bratislava)

3D model of island based MTC device

Cross sections of island based MTC device

MEMS senzor mikrovlnného výkonu

Kontrolná a snímacia časť MEMS senzora

[18] T. Lohmeyer et al.: 14th MicroMechatronics Europe Workshop, 2006, (2006)
 [19] T. Lohmeyer et al.: Sensors and Actuators A 123-124 (2005)
 (NATO SIP project)

Integrated Sensor Single-chip

Detail of MTC Device-as a "heart" of microwave transmitted power sensors

Realizácia MEMS prvku s vysokým stupňom technologickej náročnosti

- 12 litografických masiek (~ 60 samostatných technologicých krokov)
- obojstranná litografia
- submikrometrové tvarovania
- vzájomná technologická kompatibilita
- vysoká kontrolovateľnosť v povrchovom a objemovom mikro(nano)tvarovaní (~ μm)
- vypracovanie metodológie ETM charakterizácie MEMS prvkov
- vypracovanie metodológie 2D modelovania a simulácie MEMS prvkov
- podiel na vývoji 3D T-M modelu MEMS prvku – zosúladenie s komplexnou ETM experimentálnou charakterizáciou

Elektrotepelná charakterizácia MEMS prvku

[18] T. Lohmeyer et al.: 14th MicroMechatronics Europe Workshop, 2006, (2006)
 [19] T. Lohmeyer et al.: Sensors and Actuators A 123-124 (2005)

- Analýza citlivosti TS (polySi/Ni tenkovrstvový odpor) (10 nm/80 nm)
- Analýza transportných vlastností pHEMT mikrovlnných tepelných žiaríčov (AlGaAs/InGaAs/GaAs pHEMT) $L_g = 0.8 \mu\text{m}$

Konverzné charakteristiky a teplotná časová konštanta MEMS prvku

- Vysoká linearita v elektrotepelnej konverzii prvku
- Vysoká konverzná účinnosť prvku ($R_{th} \sim 10 \text{ K/mW}$)
- Rýchla teplotná odozva ($\tau \sim 1.32 \text{ ms}$) určená nezávisle tromi metódami

Termo-mechanická analýza MEMS prvku

[18] T. Lohmeyer et al.: 14th MicroMechanics Europe Workshop, 2008, (2008)
 [19] T. Lohmeyer et al.: Sensors and Actuators A, 122-124 (2005)

Štúdium intrinzičných termo-mechanických vlastností MEMS prvku – návrh metodológie (Spolupráca s MLC, Bratislava)

Termálna deformácia prvku

- Polovodičová heteroštruktúra
- Metalizačné systémy
- Dielektrická fixácia a tepelná izolácia

$\Delta T \rightarrow$ Zmena deformácie

Meranie deformácie - metódy

- Statické
 - klasická interferometria – mikrointerferometer
 - autokolimačný princíp
 - konfokálny mikroskop
- Dynamické
 - dopplerovský vibrometer

Meranie deformácie pomocou vibrometra

(Spolupráca s MLC, Bratislava)

[18] T. Lohmeyer et al.: 14th MicroMechanics Europe Workshop, 2008, (2008)
 [19] T. Lohmeyer et al.: Sensors and Actuators A, 122-124 (2005)

Merací bod:

Konfokálny 3D scanovací mikroskop

(Spolupráca s MLC, Bratislava)

[18] T. Lohmeyer et al.: 14th MicroMechanics Europe Workshop, 2008, (2008)
 [19] T. Lohmeyer et al.: Sensors and Actuators A, 122-124 (2005)

- Konfokálny mikroskop Zeiss
- 3D scanovanie s rozlíšením ~ 0,1 µm v osi z
- Rôzne vlnové dĺžky scanujúceho zdroja (450–630 nm)

Vplyv stratového výkonu na deformáciu MEMS prvku

Tepelne riadený MEMS mikroaktuátor

Po prvý krát predstavený MEMS mikroaktuátor na báze tenkých GaAs nosníkov (8 µm)

MEMS aktuátor na báze GaAs nosníkov s hrúbkou 8 µm (pohľad z aktívnej strany)

Aktuátor budovaný rí výkonom