Schottky Diode RF-Detector and Focused Ion Beam Post-Processing

MURI Annual Review

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Outline

- Operation and characteristics of Schottky power detector
- Mask layout for Schottky diodes
- Fabricated Schottky diodes with n+ substrate with n-epi layer on top
- Schottky diodes by CMOS process
- RF radiation test
- Schottky diodes by using Focused ion beam technology
- Schottky diodes designed for MOSIS standard CMOS process
- Conclusion and future work

Original Project Objectives:

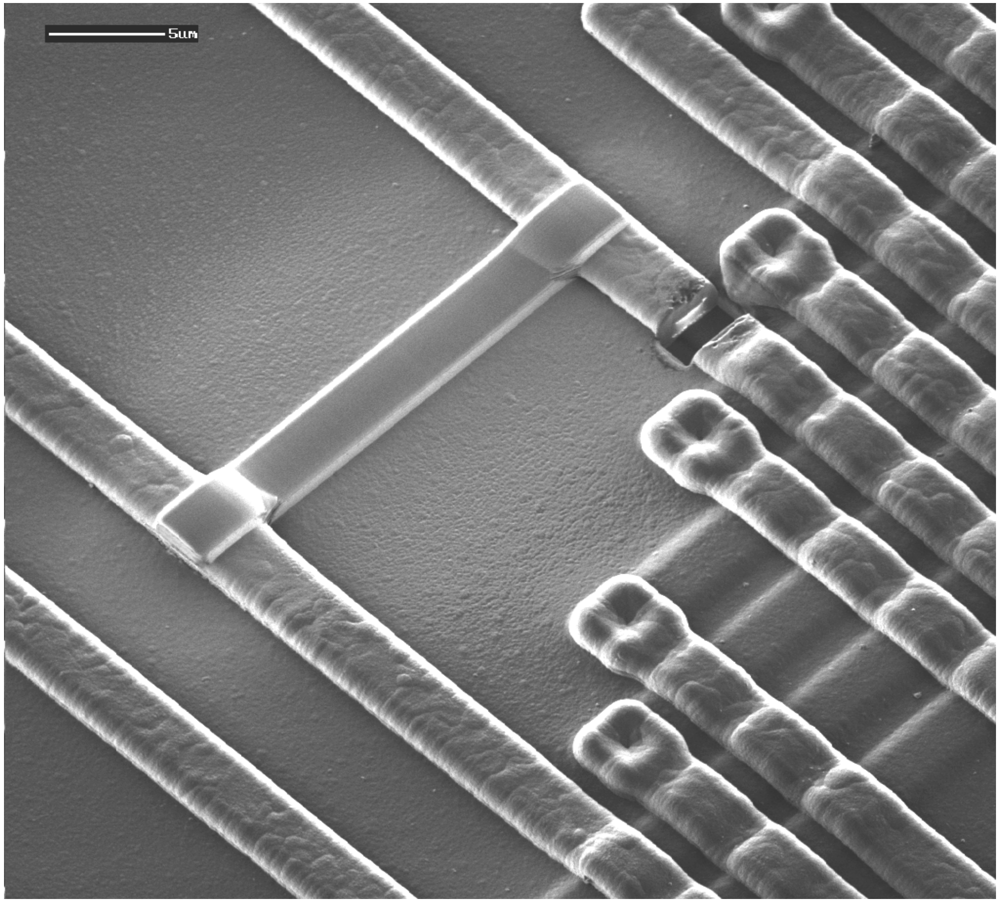
- Direct analog microwave level measurement on a chip using
  - a) Schottky diodes
  - b) Thermal detectors
- Incorporation of RF detectors on chips, including FIB diode fabrication on existing chips

- Focused ion beam diagnosis circuit restructuring and device diagnosis by burned out element sectioning

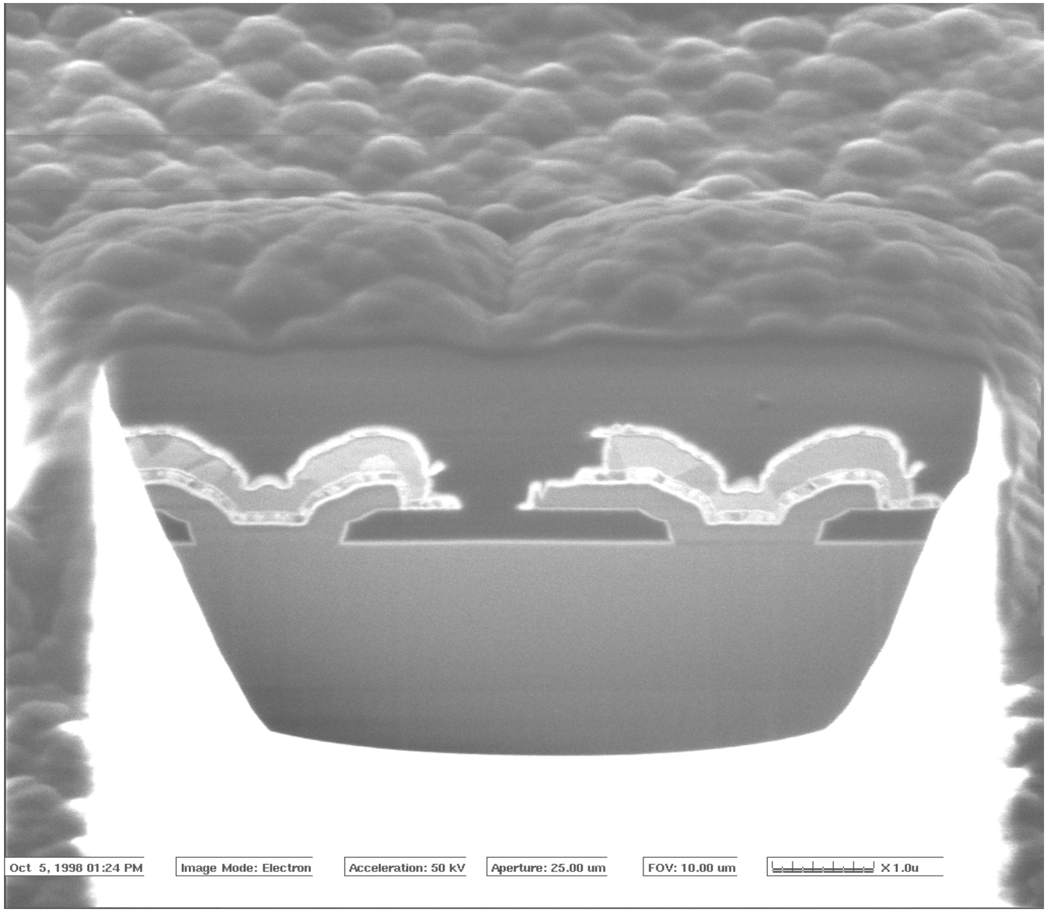
Changes to Objectives:

- Thermal detectors not pursued

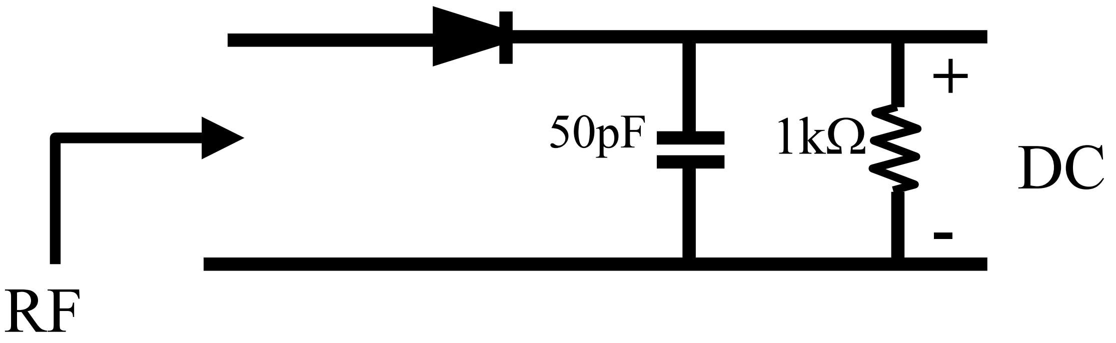
Example of FIB Circuit Rewiring: Cut and Jumper

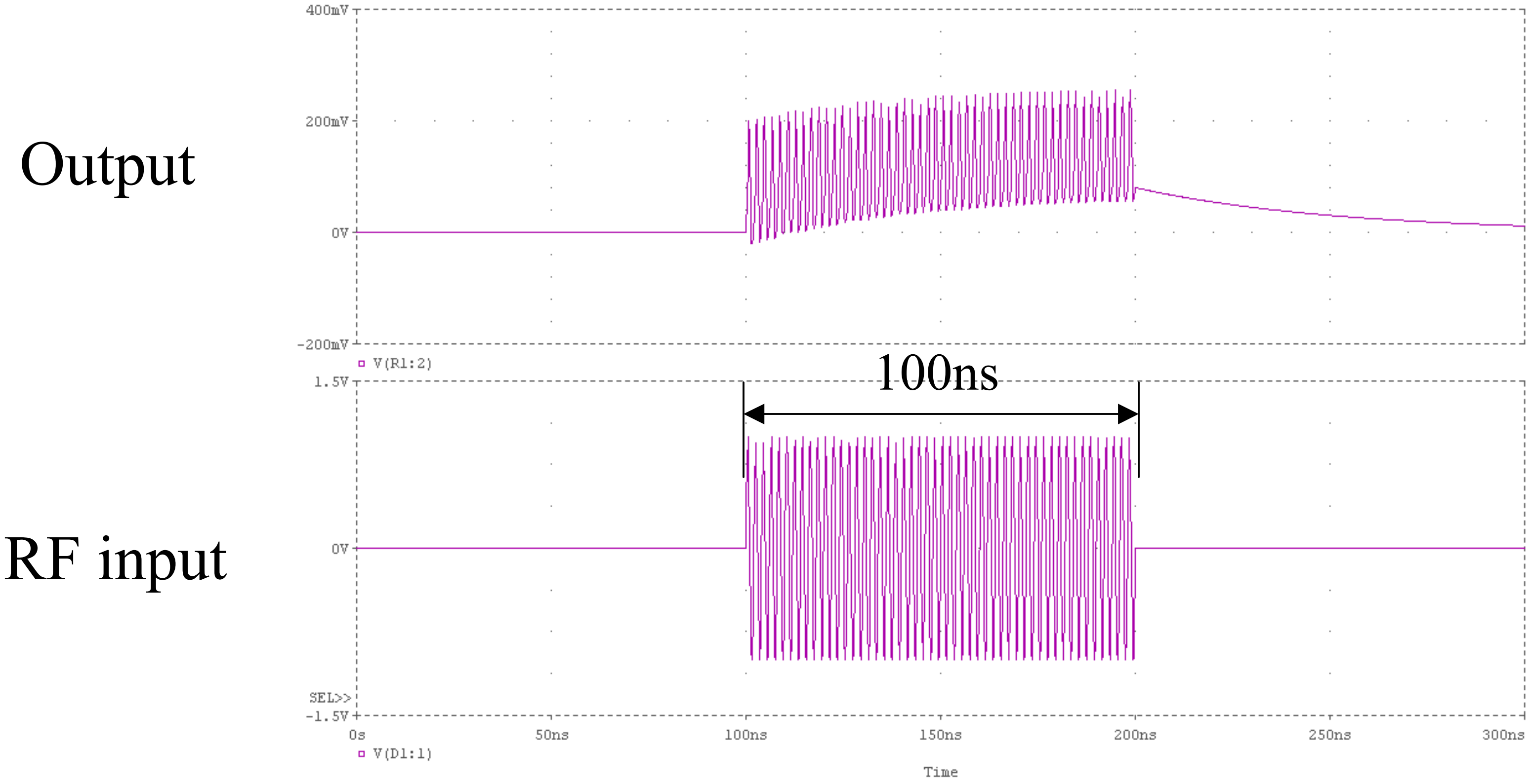


FIB-Milled Circuit Cross Section



Operation of RF Power Detector





Key factors limiting maximum frequency

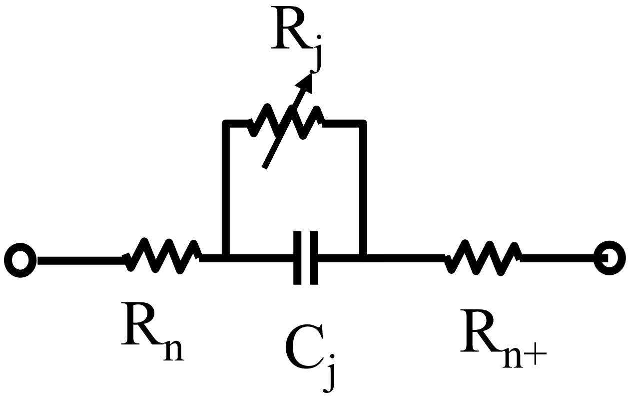
- Junction capacitance

$$C_j = A\sqrt{\frac{\varepsilon q N_d}{2(V_a + V_d)}}$$

➔ A: contact area, N_d: doping concentration
V_a: applied voltage, V_d: built in voltage

- Junction resistance:

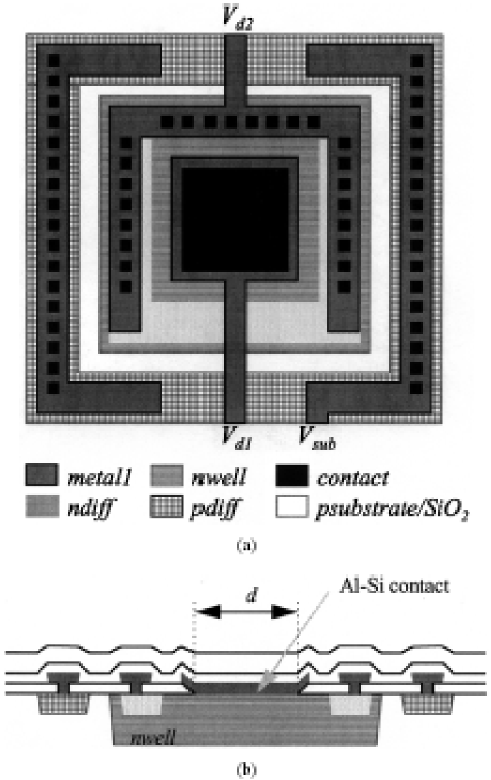
$$\frac{1}{R_j} = \frac{dI_x}{dV_a} = AI_s \frac{q}{nkT} \exp\left(\frac{qV_a}{nkT}\right)$$



- Equivalent circuit

- Series resistance = $R_n + R_{n+}$, $R_n = R_o/A + \mathbf{R_1/A^{1/2}}$
  ➔ $R_n >> R_{n+}$ (>> R_j , after turning on)
  ➔ Series resistance mainly determined by R_n(n layer resistance).
- RC time constant $\propto A^{1/2}$(due to spreading resistance), $R_n(N_d)$, etc.
- Objective ➔ Reduce junction capacitance(C_j) => decrease contact area
  Reduce series resistance => minimize n layer thickness

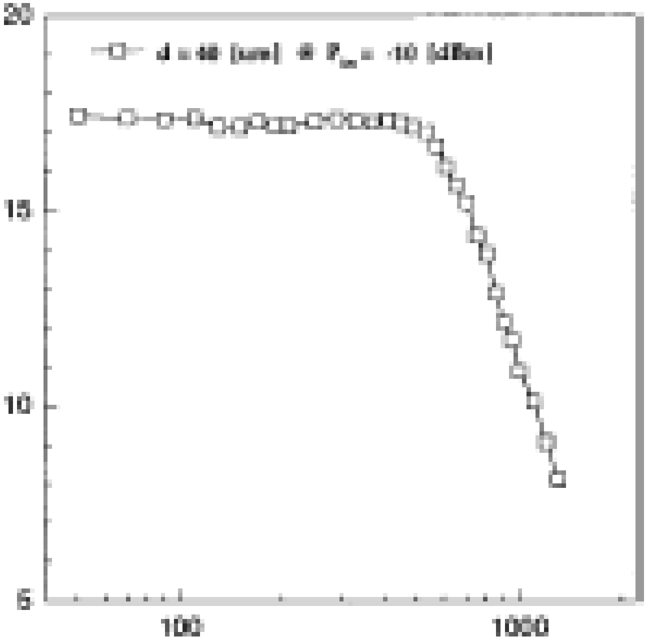
Schottky diode fabricated in MOSIS



(a)

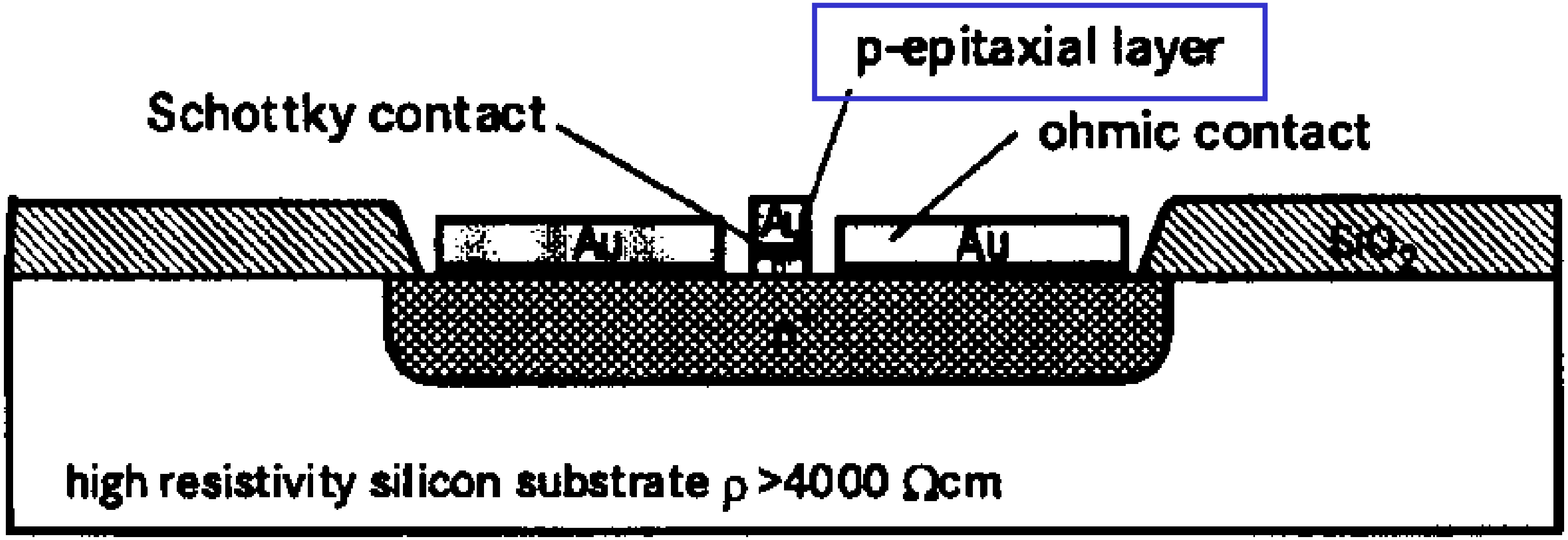
(b)

Fig. 1. (a) CAD layout of the Schottky diode with accompanying guard ring (b) cross section showing Al-Si Schottky contact.



V. Milanovic, M. Gaitan, J.C. Marshall M. E. Zaghloul,
IEEE Trans. Electr. Devices **43**, 2210 (Dec. 1996)

Coplanar Schottky Diode Developed for Rectifying Antennas



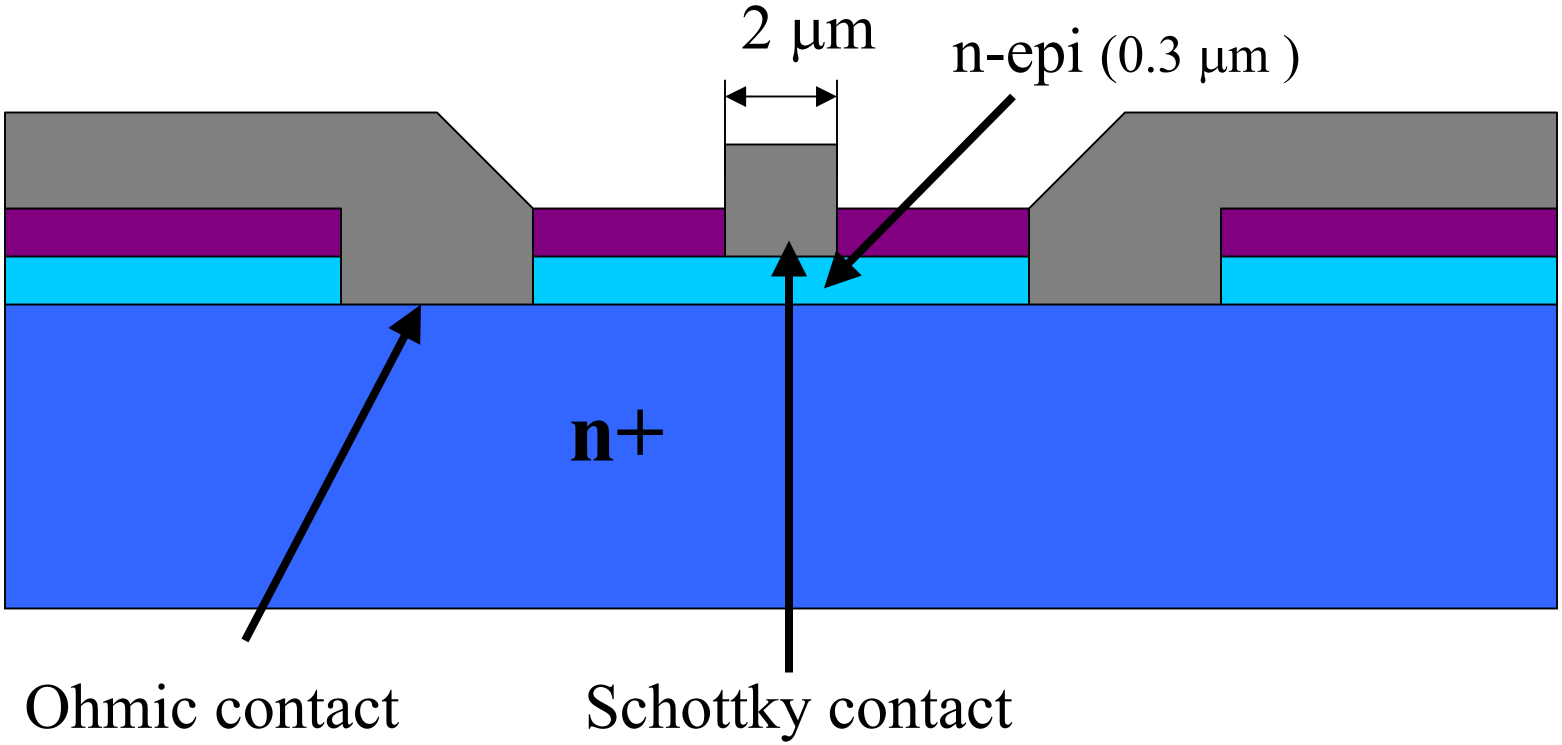
K.M. Strohm, J. Buecher, & E. Kasper ,

Daimler Benz Research, Ulm

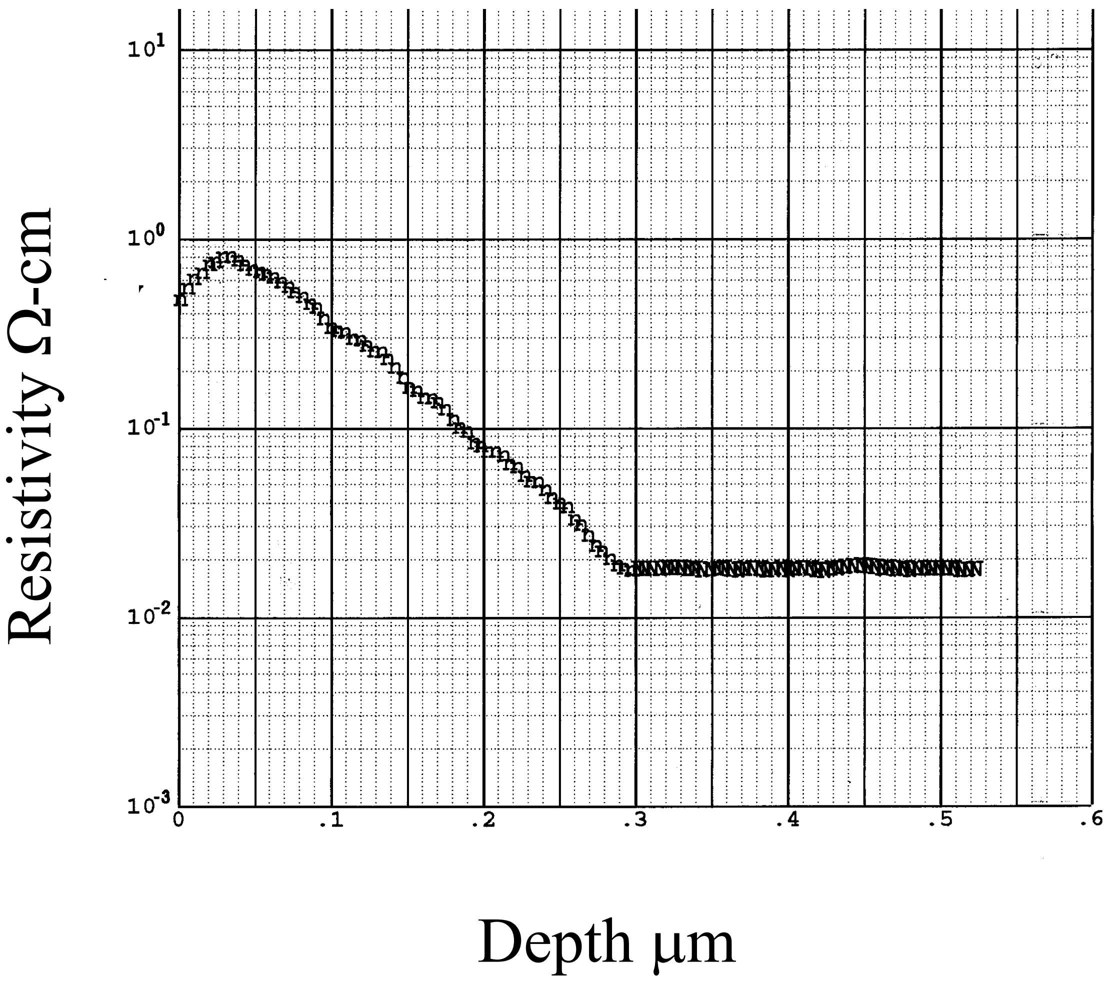
IEEE Trans. MTT Vol.46, 669, (May, 1998)

Proposed structure using n+ substrate with n-epi layer on top

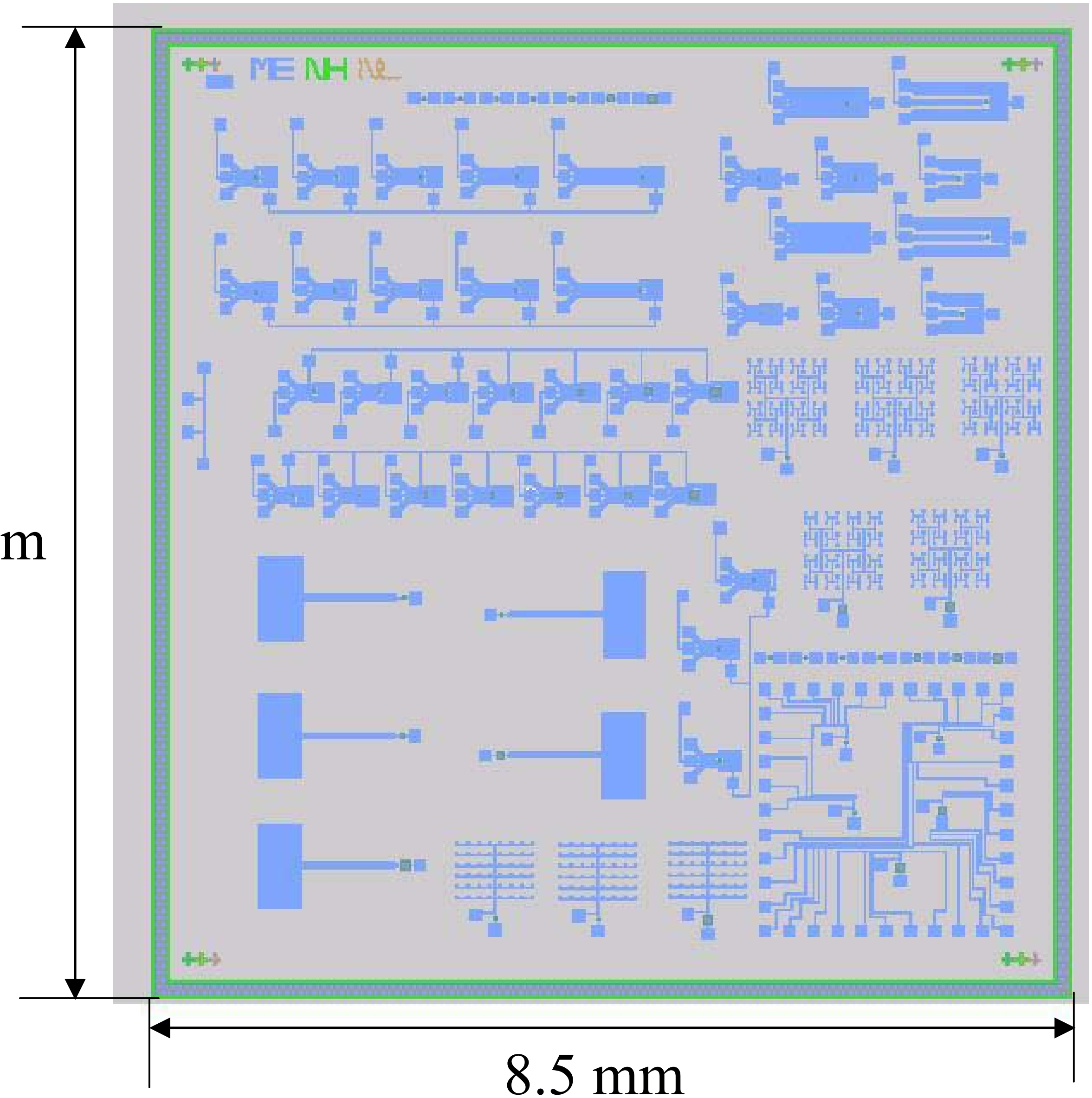
- Reduce series resistance => use n+ substrate
- Reduce contact capacitance => decrease contact area



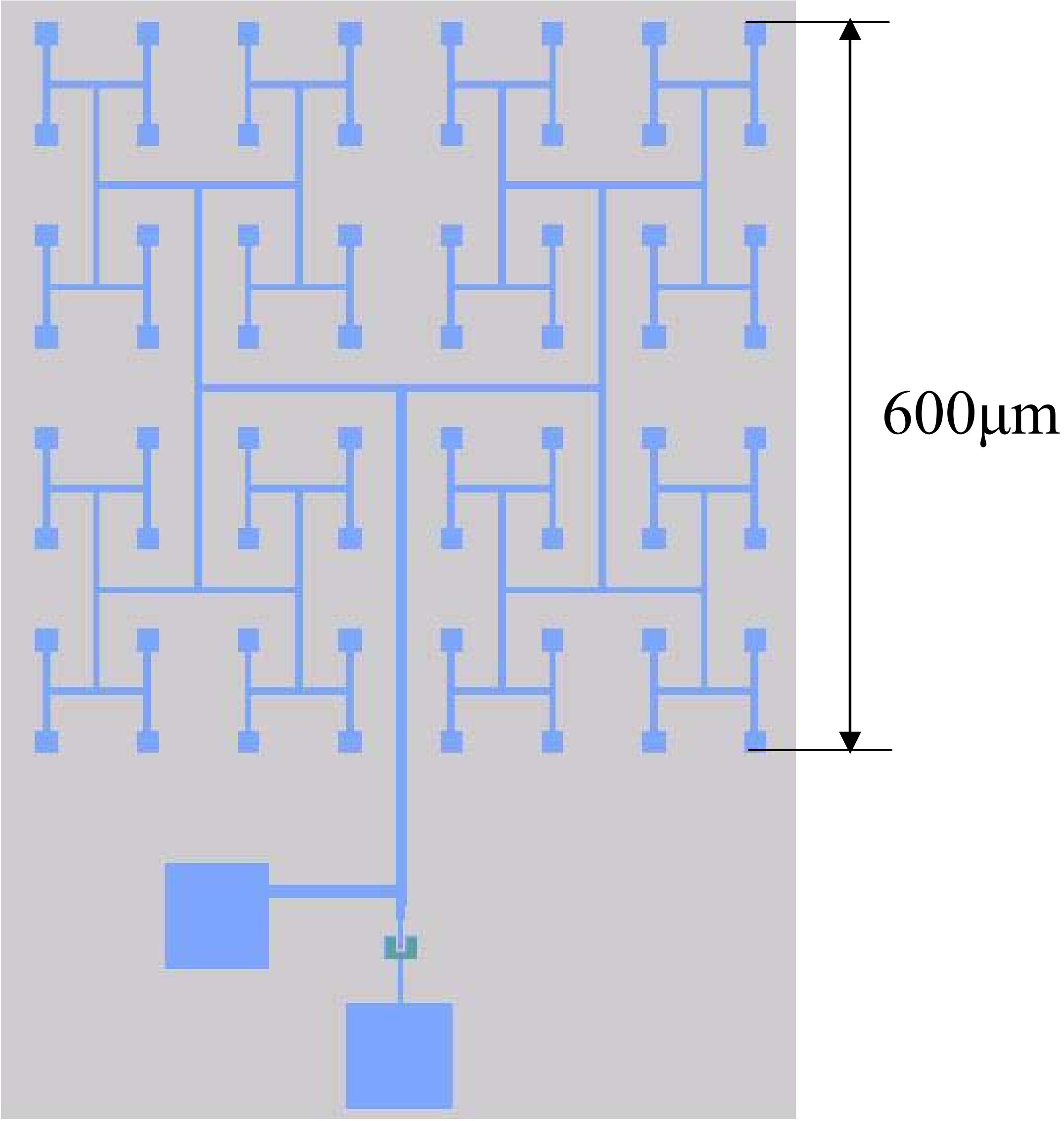
Resistivity vs. Depth of n on n$^+$ Layer



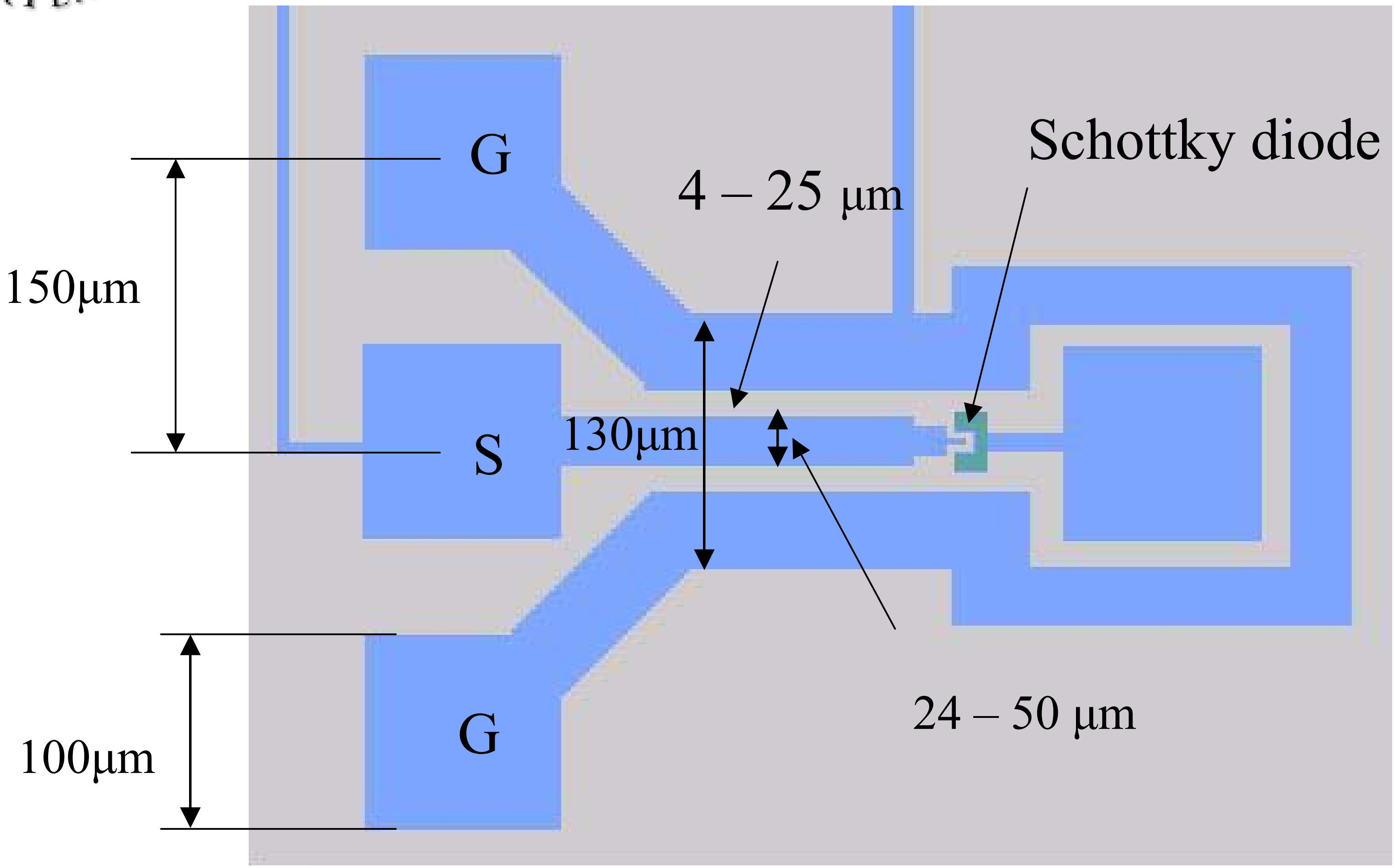
Mask layout



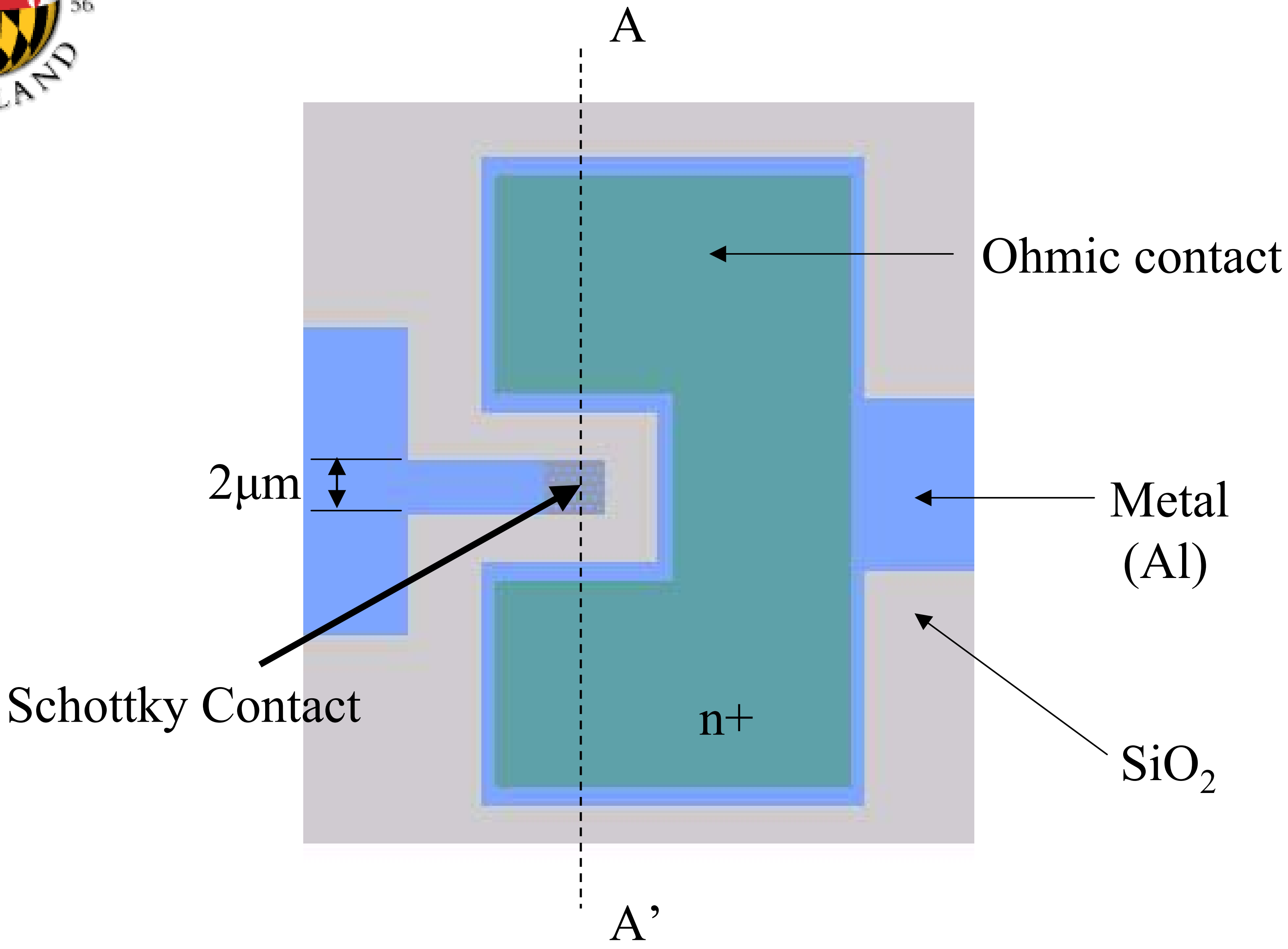
Schottky diode with clock tree



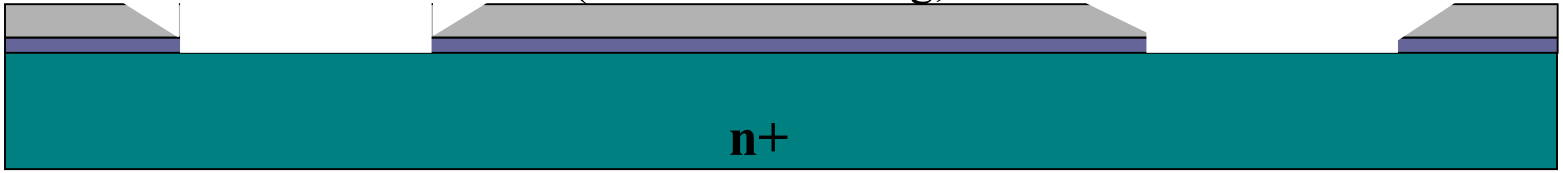
Schottky diode with 150µm pitch pads



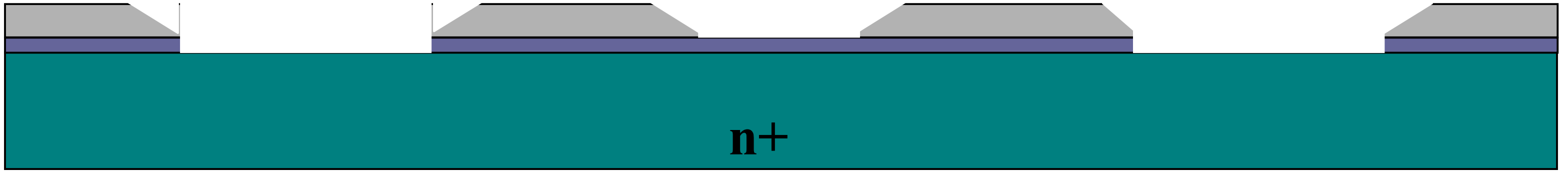
Schottky Diode layout



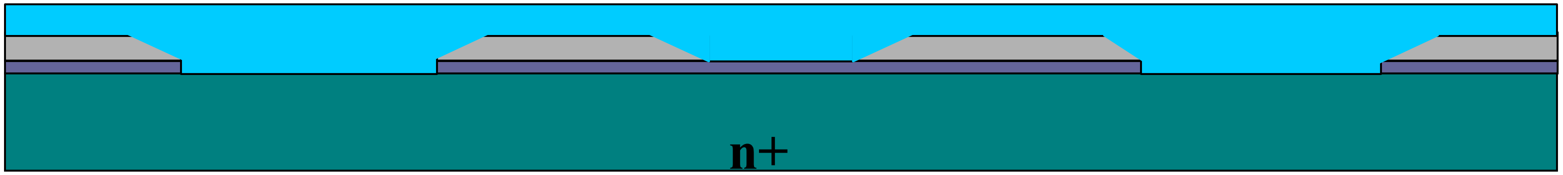
Etch SiO2 and 0.3um n silicon layer with n-high mask
(SiO2: wet etching, n-Si: RIE)



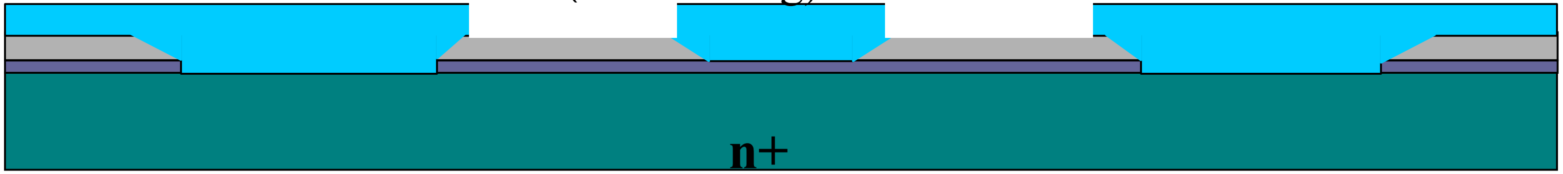
Etch SiO2(wet etching) with n-low mask



Deposit 0.5um Al with E-Beam evaporator

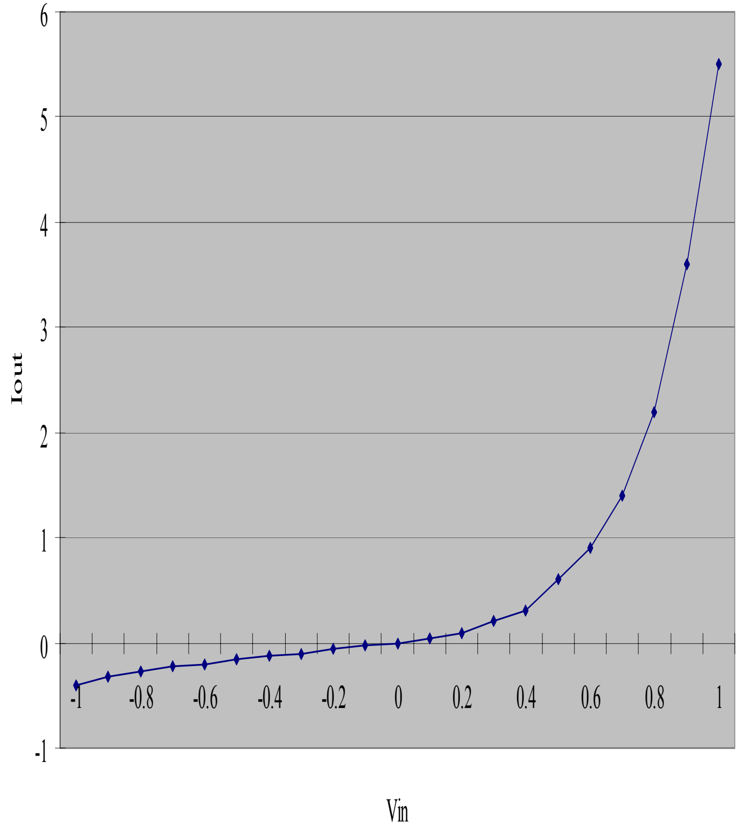


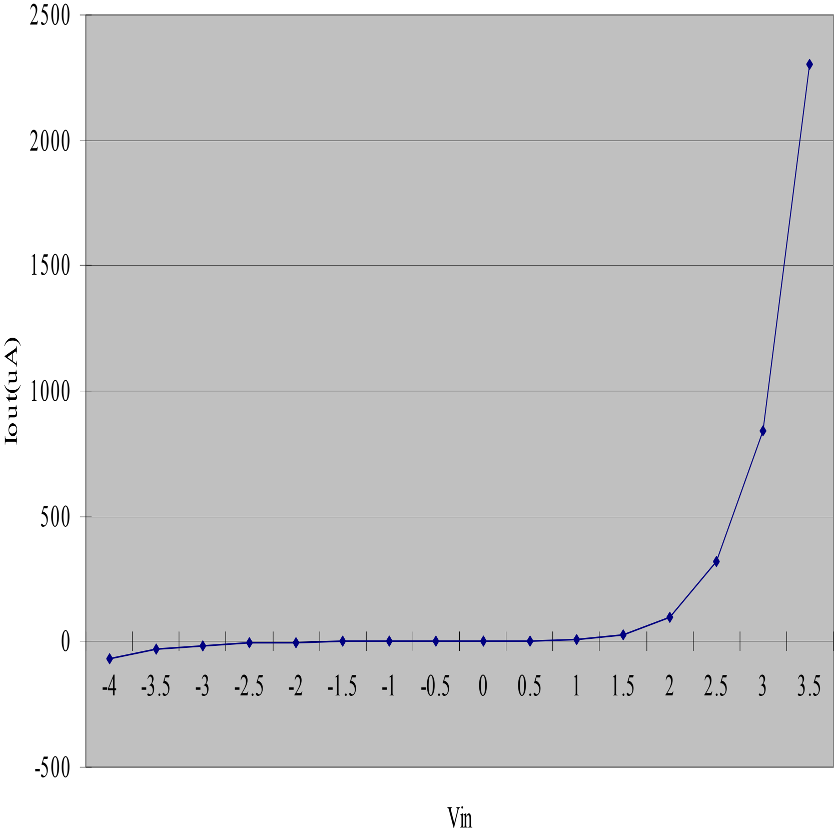
Etch Al(wet etching) with metal mask



Measured result I (DC)

- DC Characteristics(2μm x 2μm by RIE, I-V curve)





➔**Exponential change of contact resistance**

$R_j >> R_s$

➔linear series resistance

$R_s >> R_j$

Measured result II (RF)

- 2μm x 2μm contact area diodes are tested.

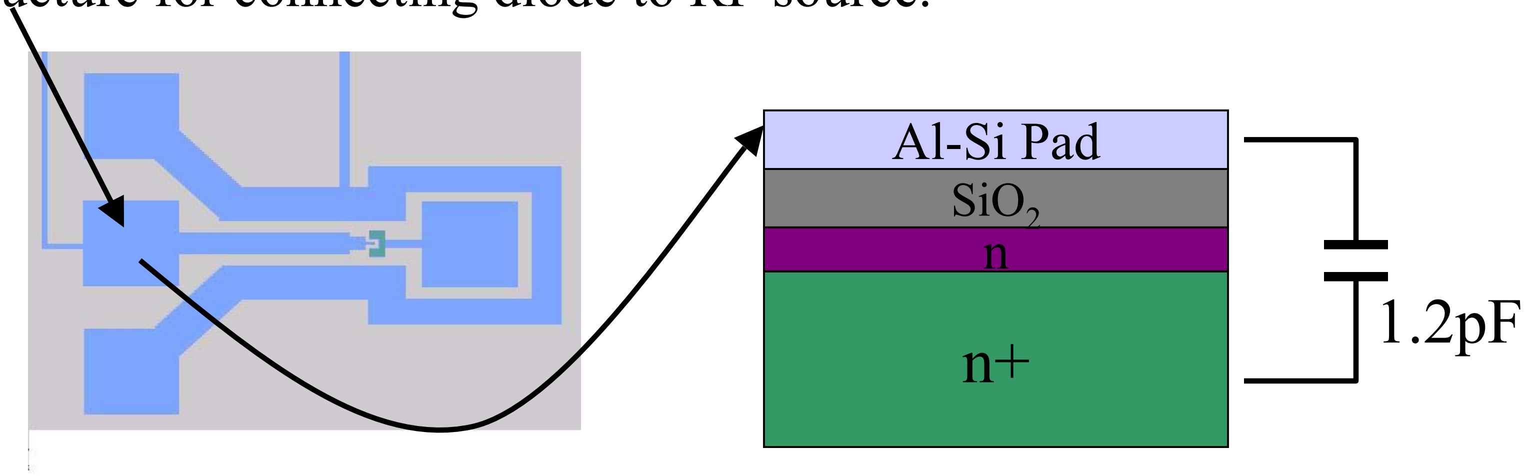
➔ These diodes worked at the power level from -10 dBm to 10 dBm

➔ DC output was linearly changed by changing power level.

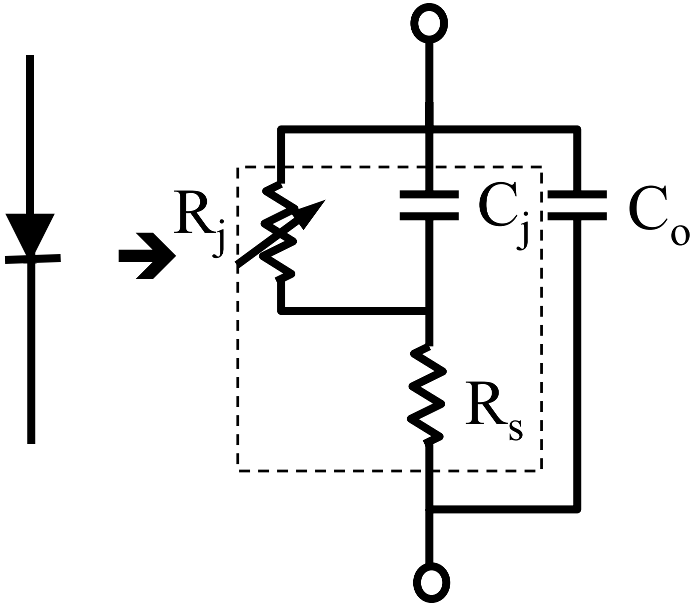
➔ Observed diode response up to 5GHz

➔ These diodes could detect RF power level, but because of the direct capacitance connection between anode and cathode of diode, the output DC voltage substantially depended on frequency.

This huge capacitance (1.2 pF by calculation) comes from pad structure for connecting diode to RF source.



Equivalent circuit



Rj: Junction Resistance

Cj: Junction capacitance

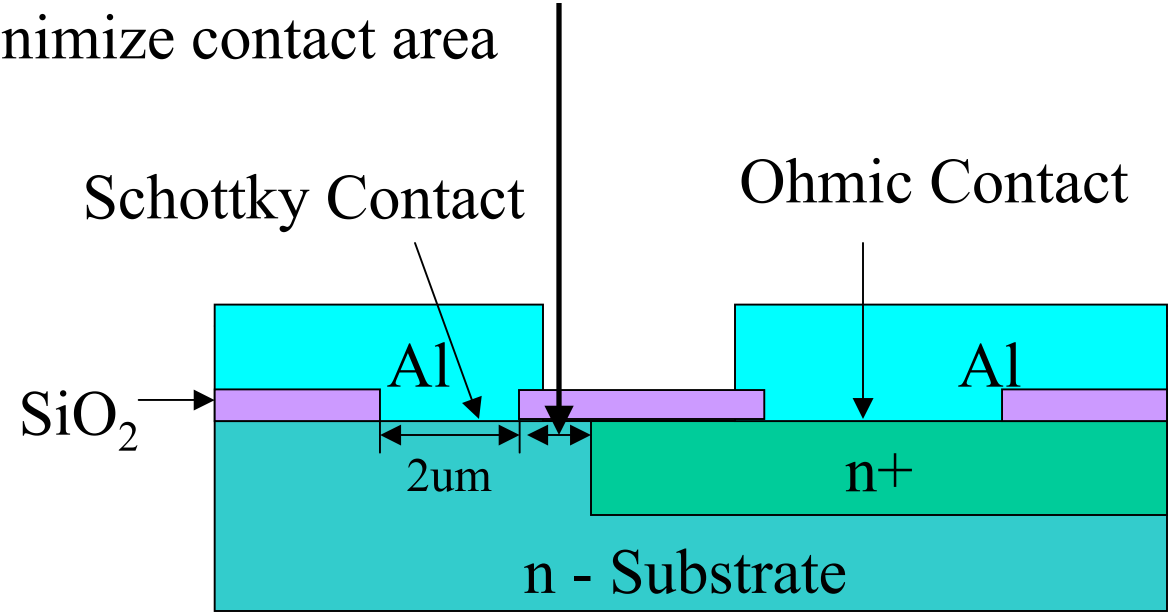
Rs: Series resistance (Rs_n + Rs_{n+})

C_o : Overlay capacitance between Al-Si pad and n+ layer

- Overlay capacitance gives direct path between anode and cathode of Schottky diode.

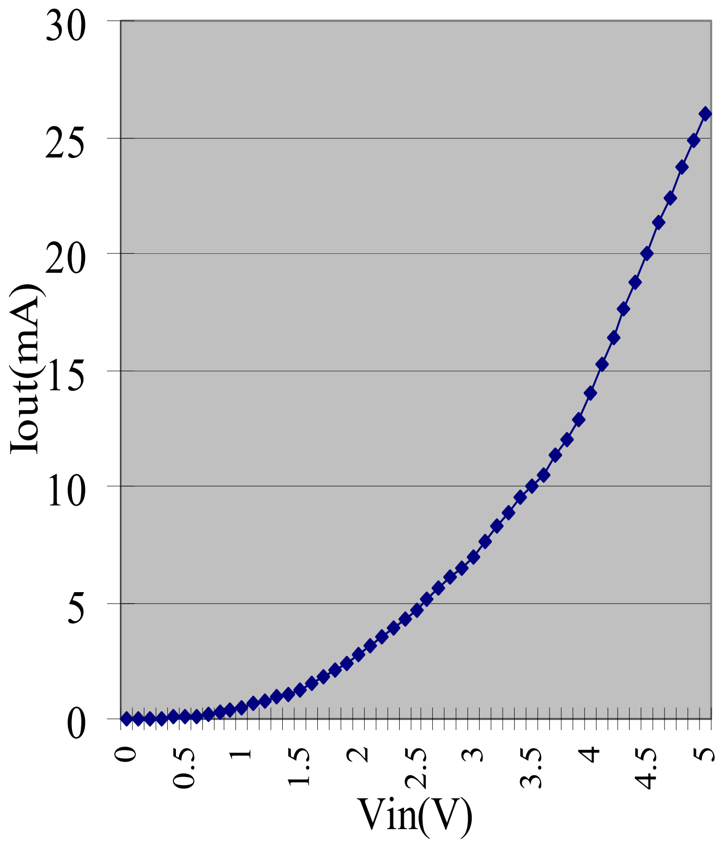
Schottky diode Design for CMOS process

- ➔ To remove the effect of Co, different substrate which has higher resistivity rather than n+ substrate should be used.
- ➔ Design new diode structure to minimize series resistance of n layer without using Silicon Molecular Beam Epitaxy(Si-MBE)
- ➔ Minimize contact area



Measured result (DC)

2x2 patch I-V



- Voltage range: -5V ~ 5V. (From –5V to 0V , current output was 0)

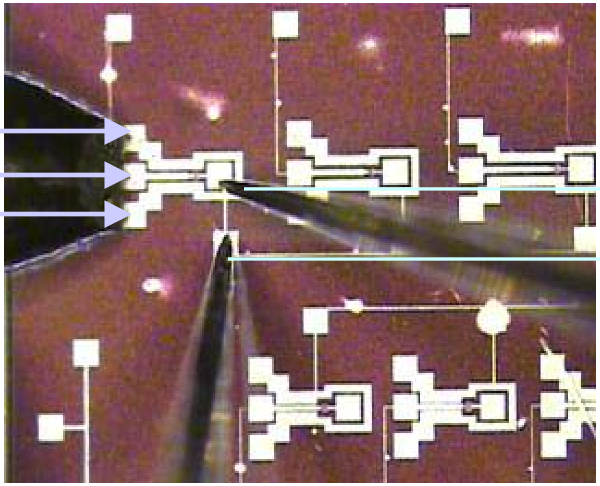
- Series resistance(between 4V and 5V) ≅ 83Ω

RF direct injection test

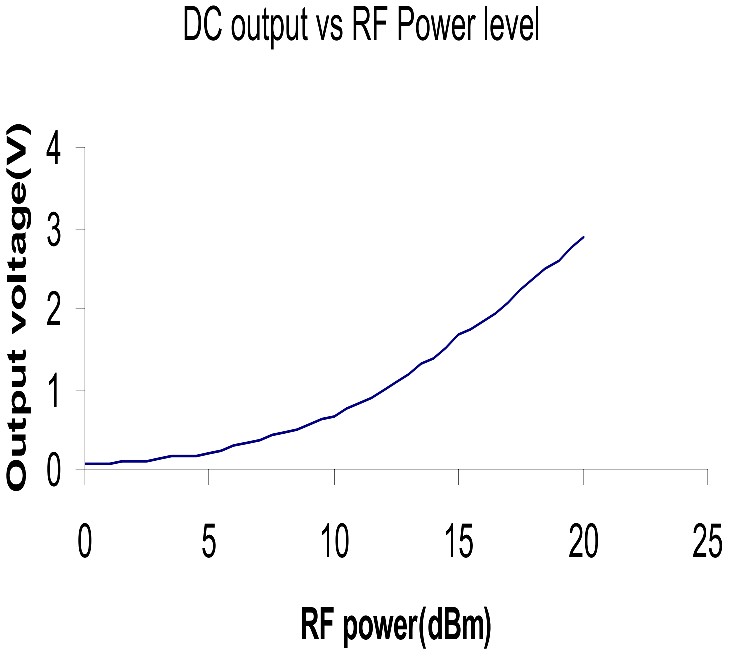
(50µm x 50 µm contact area)

RF input:
Cascade
probe

G
S
G

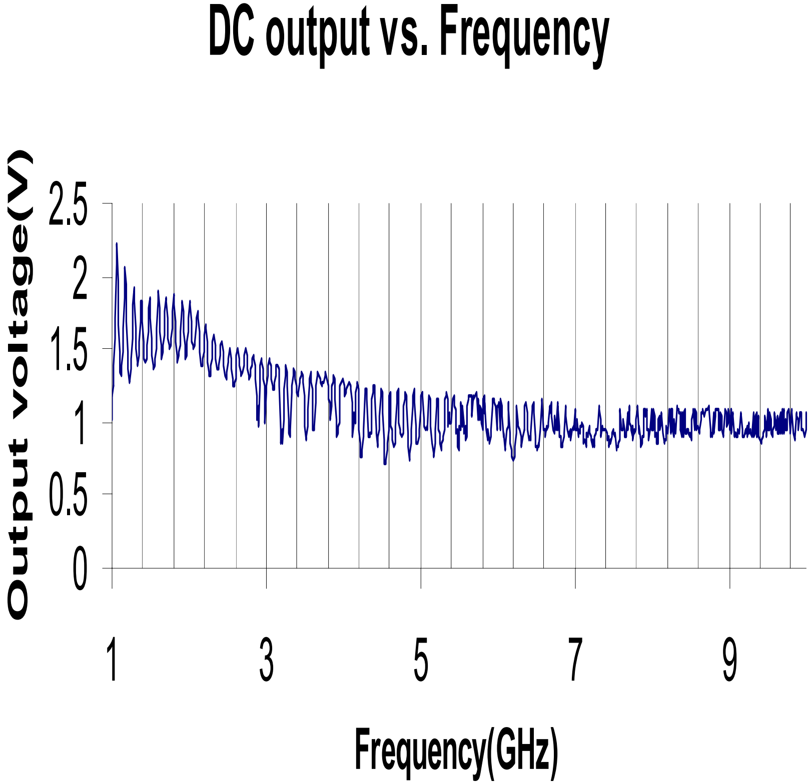


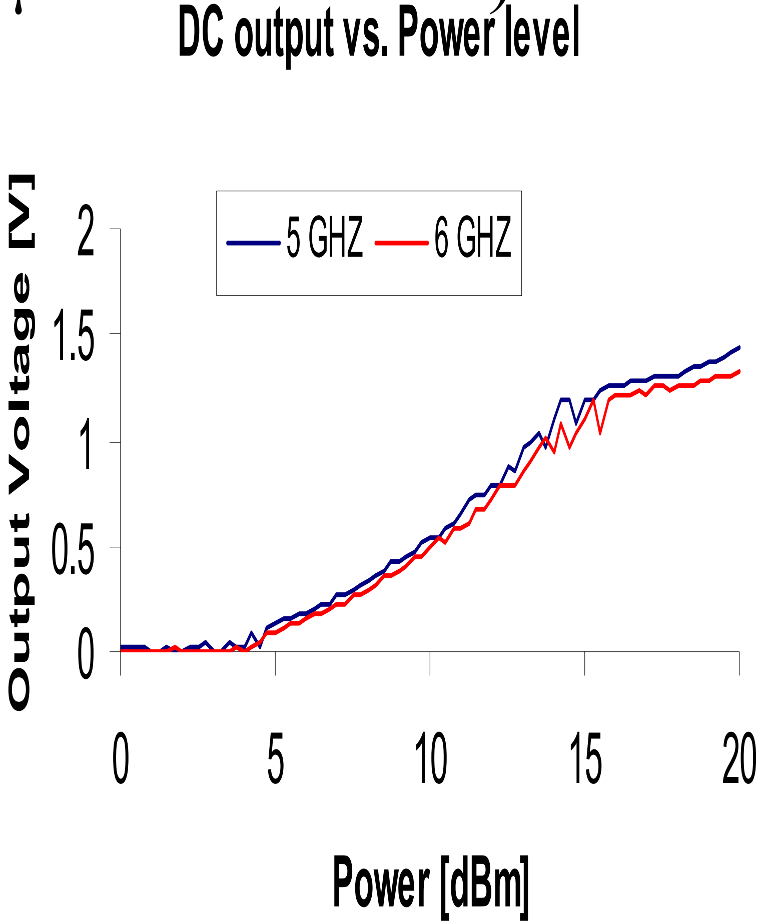
DC
output



RF direct injection test

(2µm x 2 µm contact area)

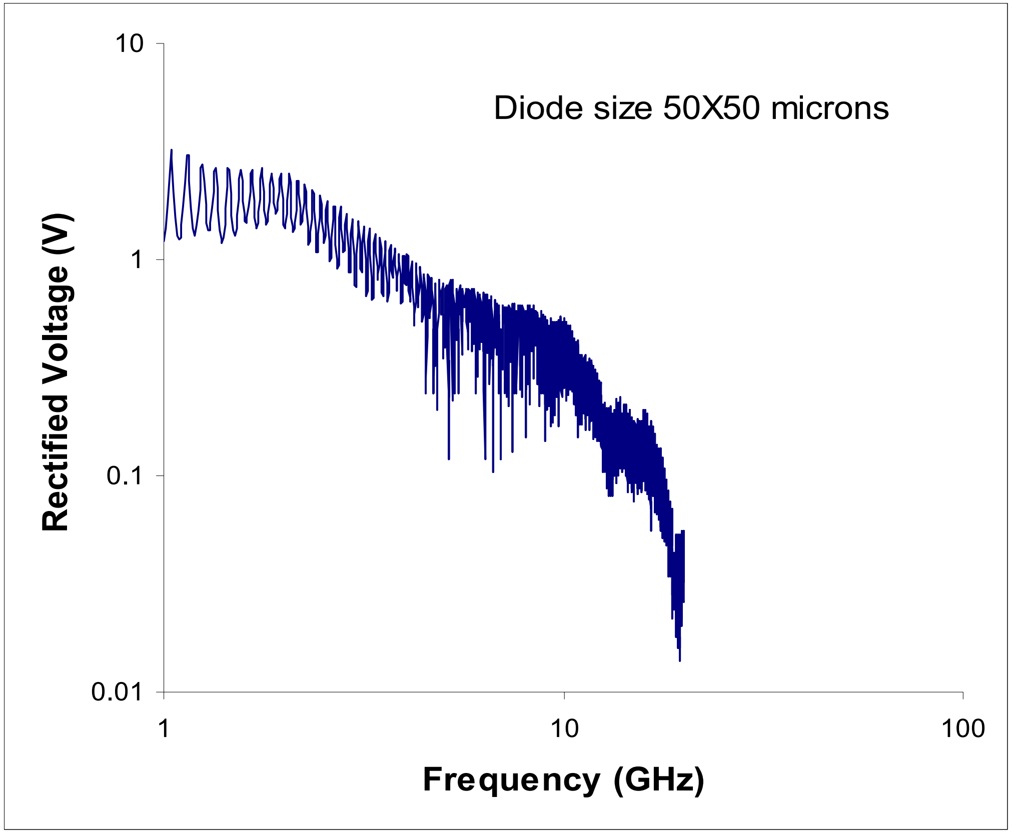

DC output vs. Frequency


DC output vs. Power level

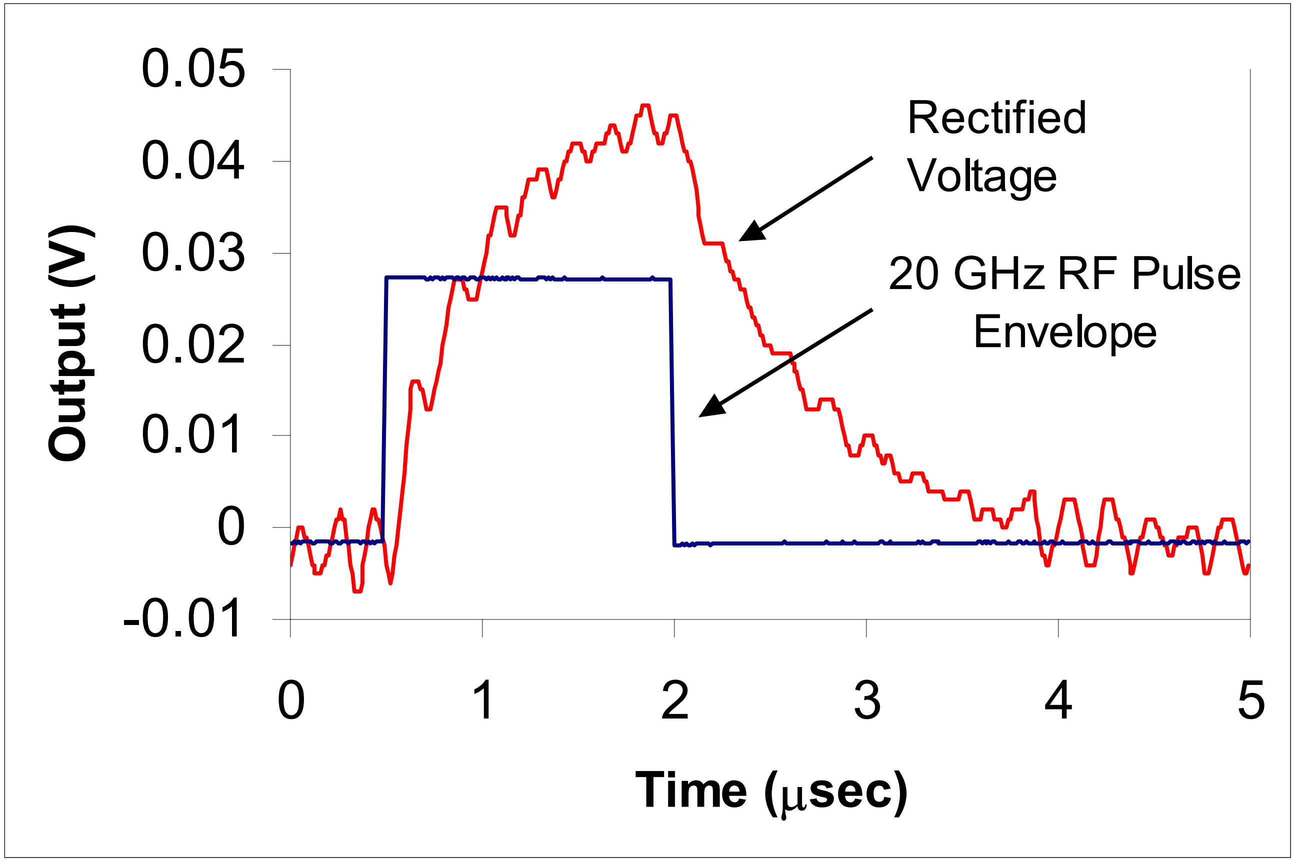
➔ **Flat response at high frequency range**

RF direct injection test

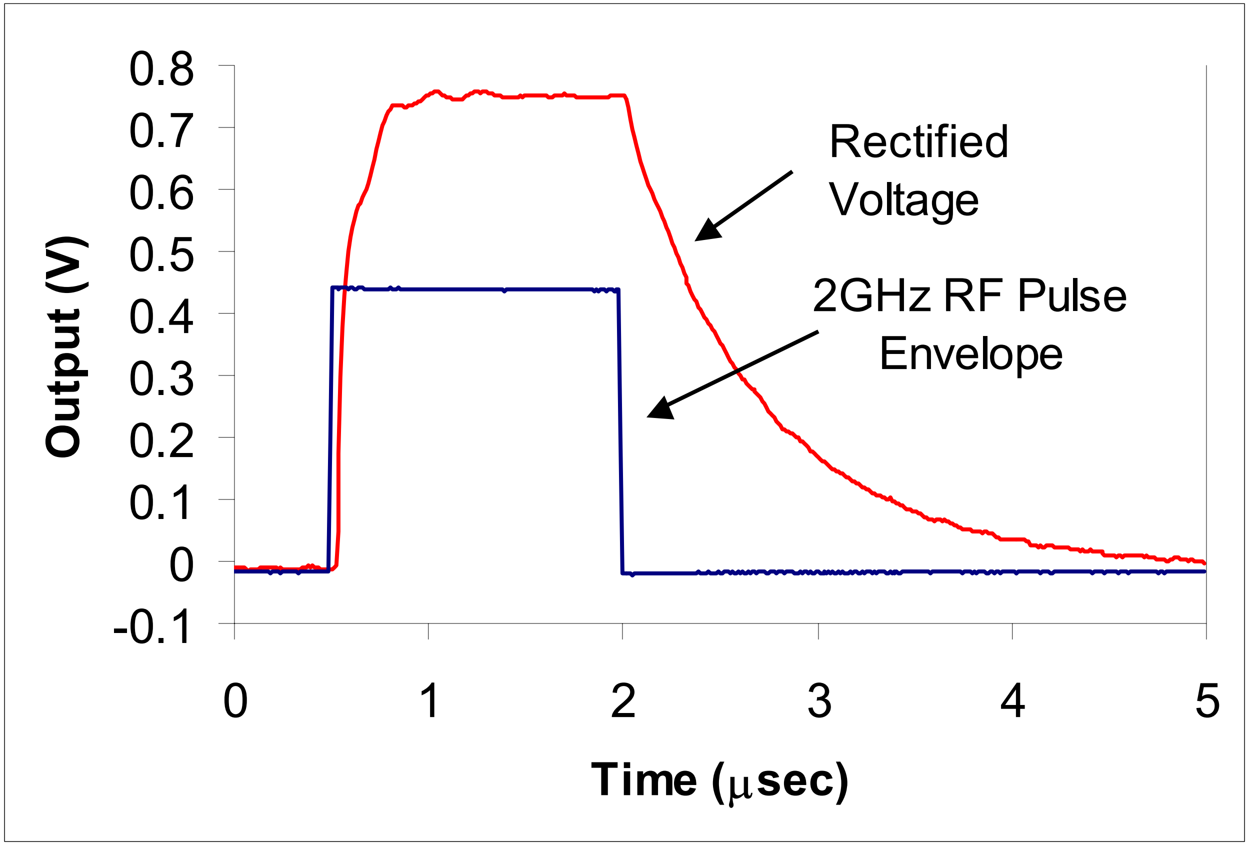
(50μm x 50 μm contact area)



Output Voltage Pulse in Response to 20 GHz. RF Burst

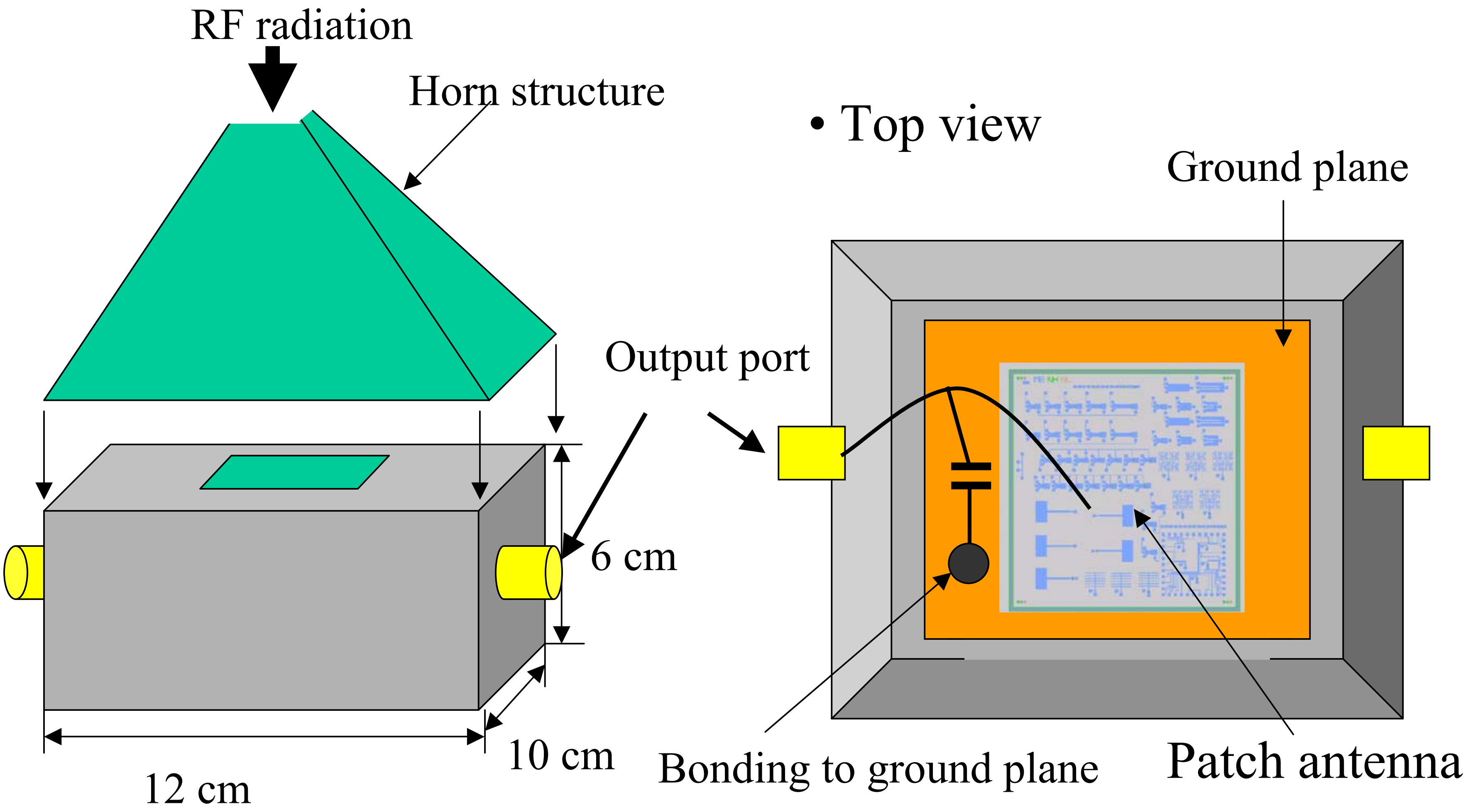


Output Voltage Pulse in Response to 2GHz.RF Burst



RF radiation test on a patch antenna structure

12cm x 10cm x 6cm size box is used for radiation test



RF radiation

Horn structure

- Top view

Ground plane

Output port

6 cm

10 cm

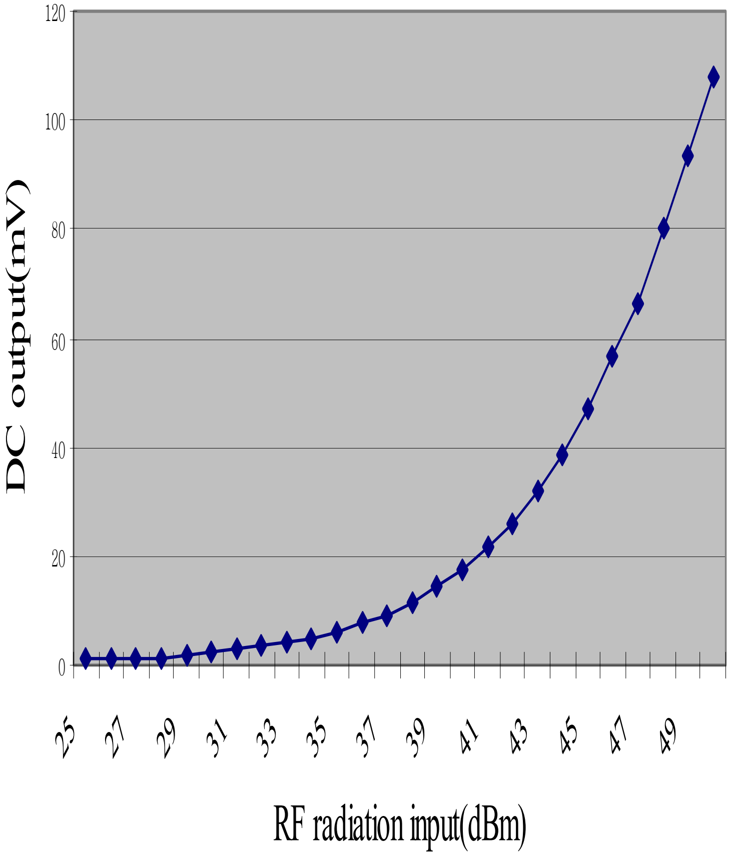
12 cm

Bonding to ground plane

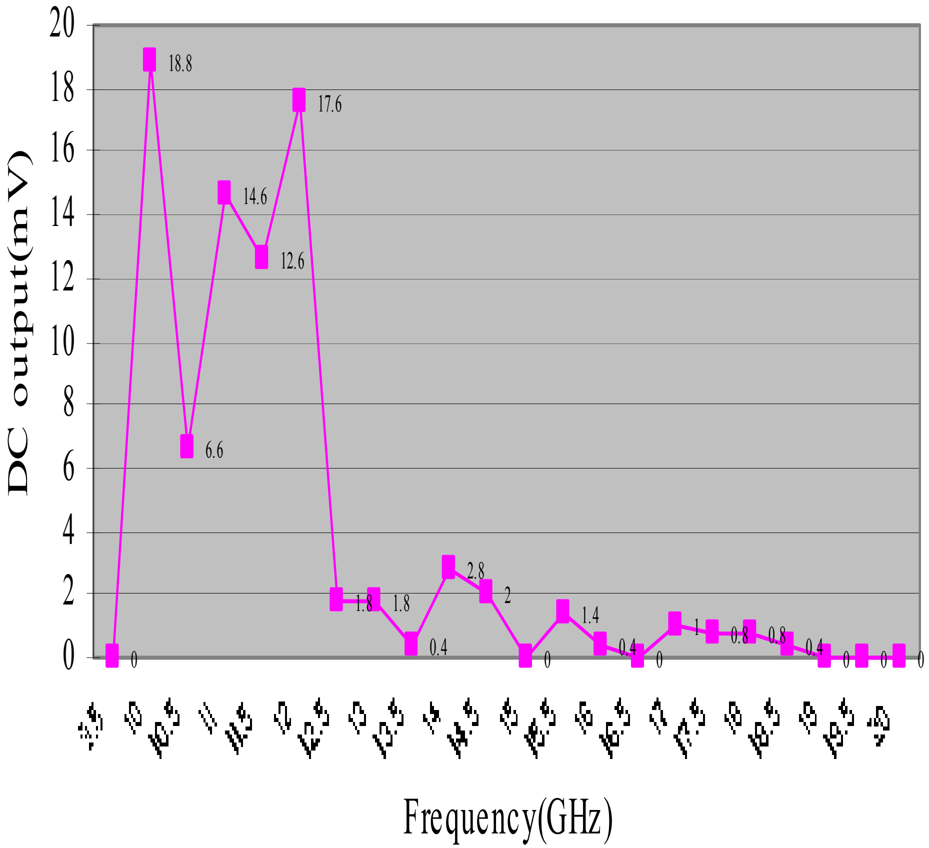
Patch antenna

RF radiation test result

Rf_in vs. Vdc_out (frequency = 12 GHz)

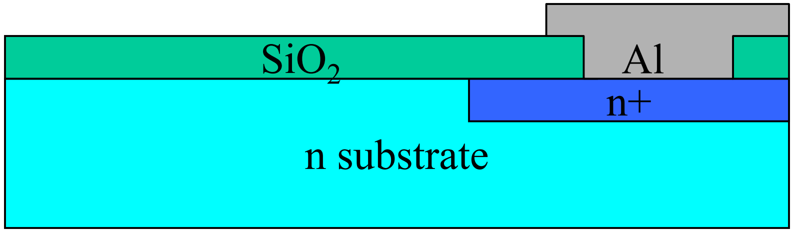


Frequency vs. DC output (RF power = 40dBm)

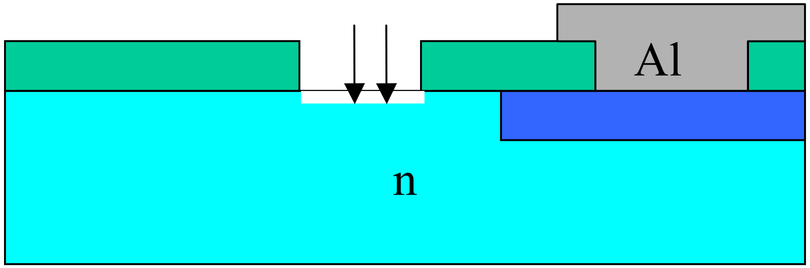


Roll-off frequency ≃ 12 GHz

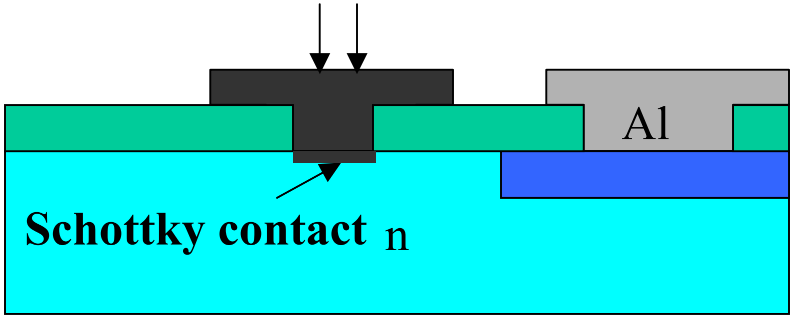
Fabricating Schottky diodes by FIB



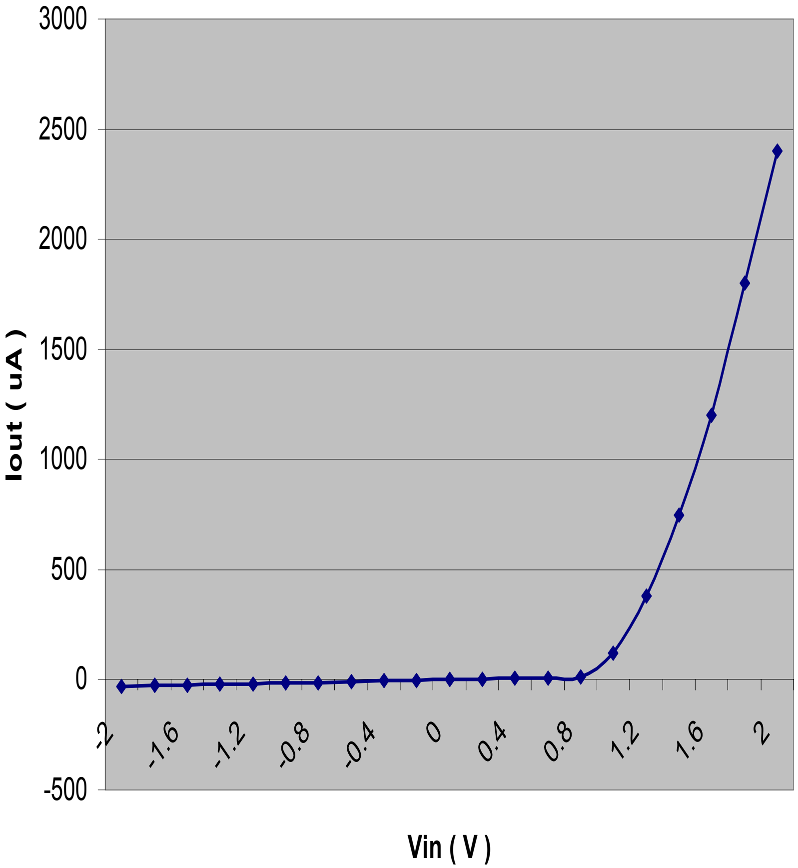
FIB milling



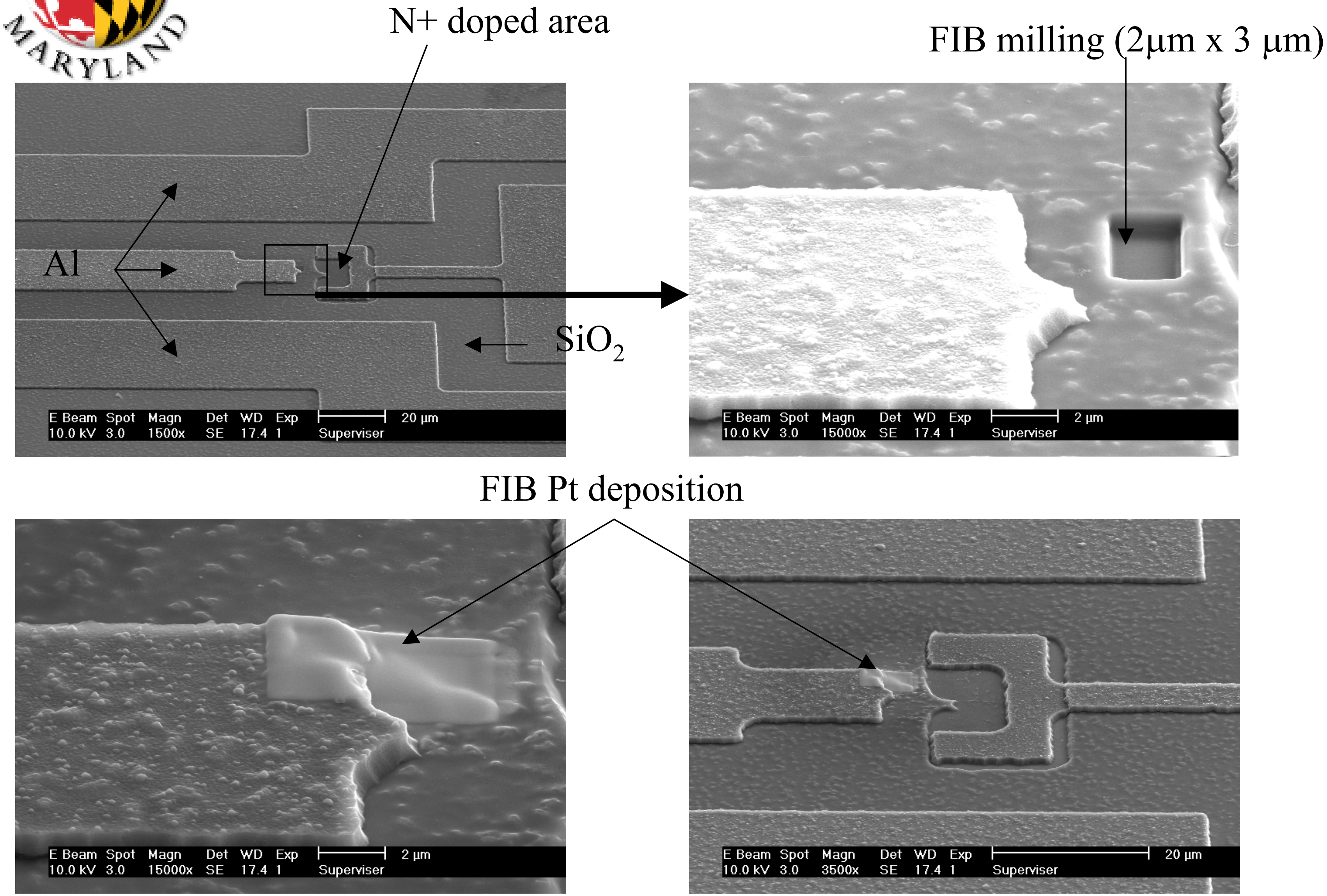
FIB Metal(Pt) deposition



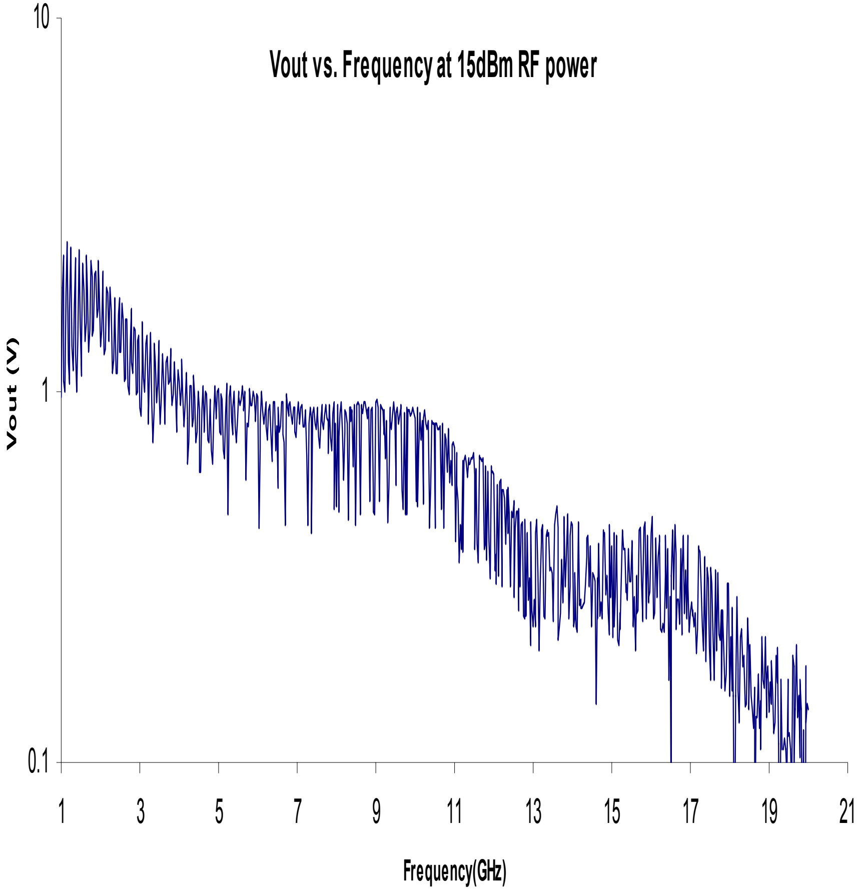
Measured result(IV curve)



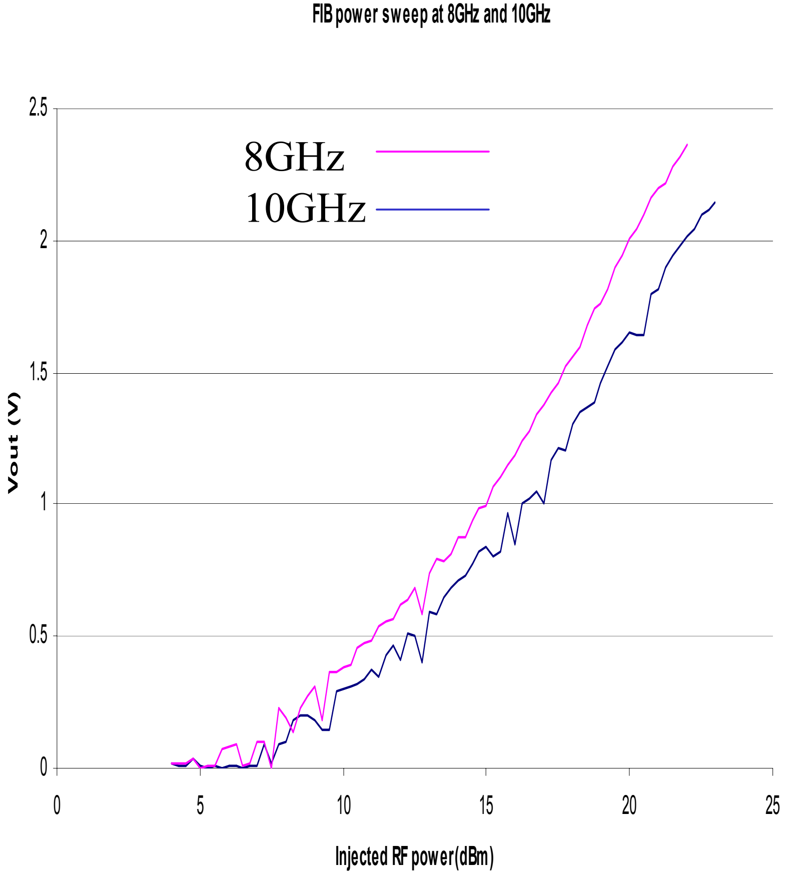
Fabrication of Schottky diode by FIB



RF direct injection test of FIB diode

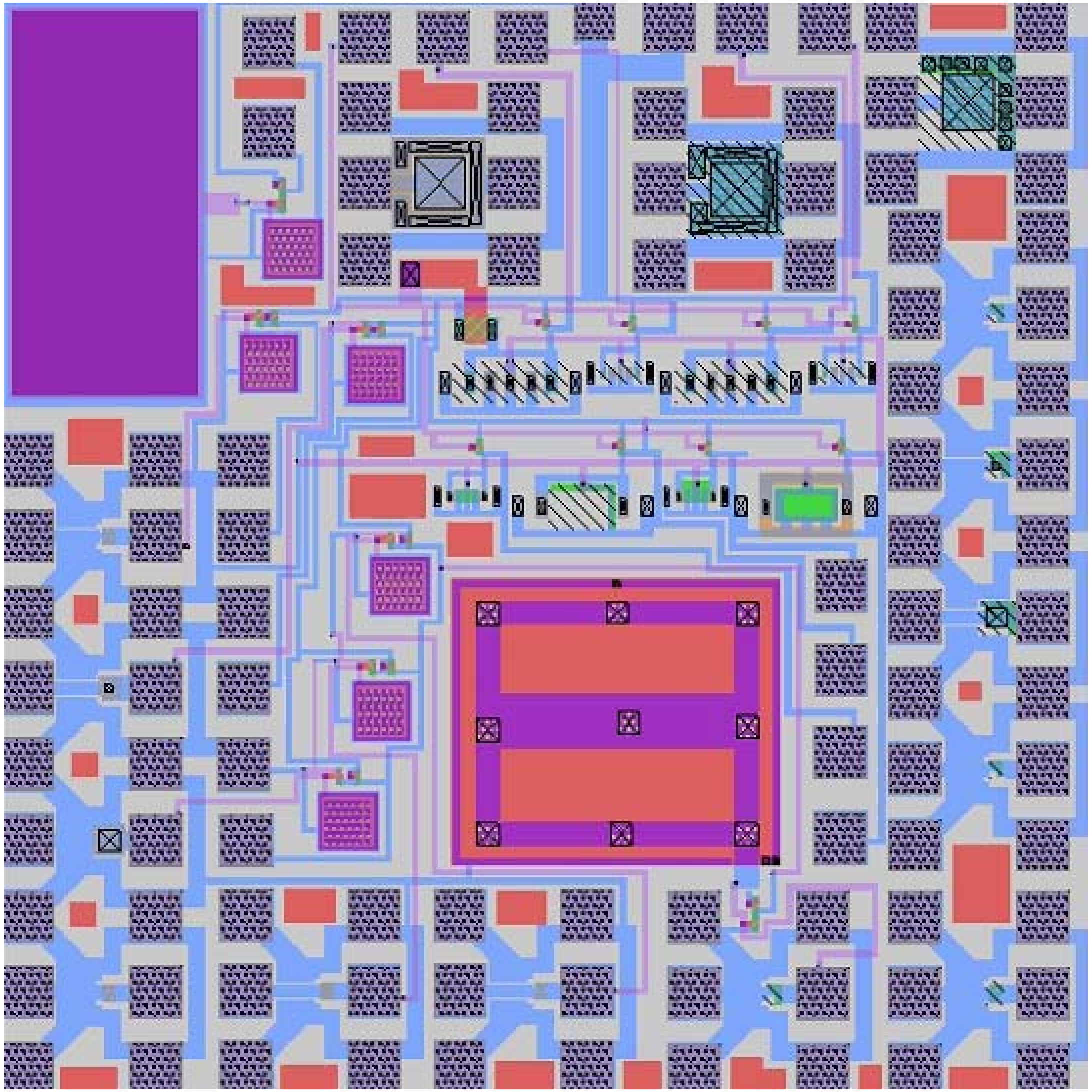


Vout vs. Frequency sweep

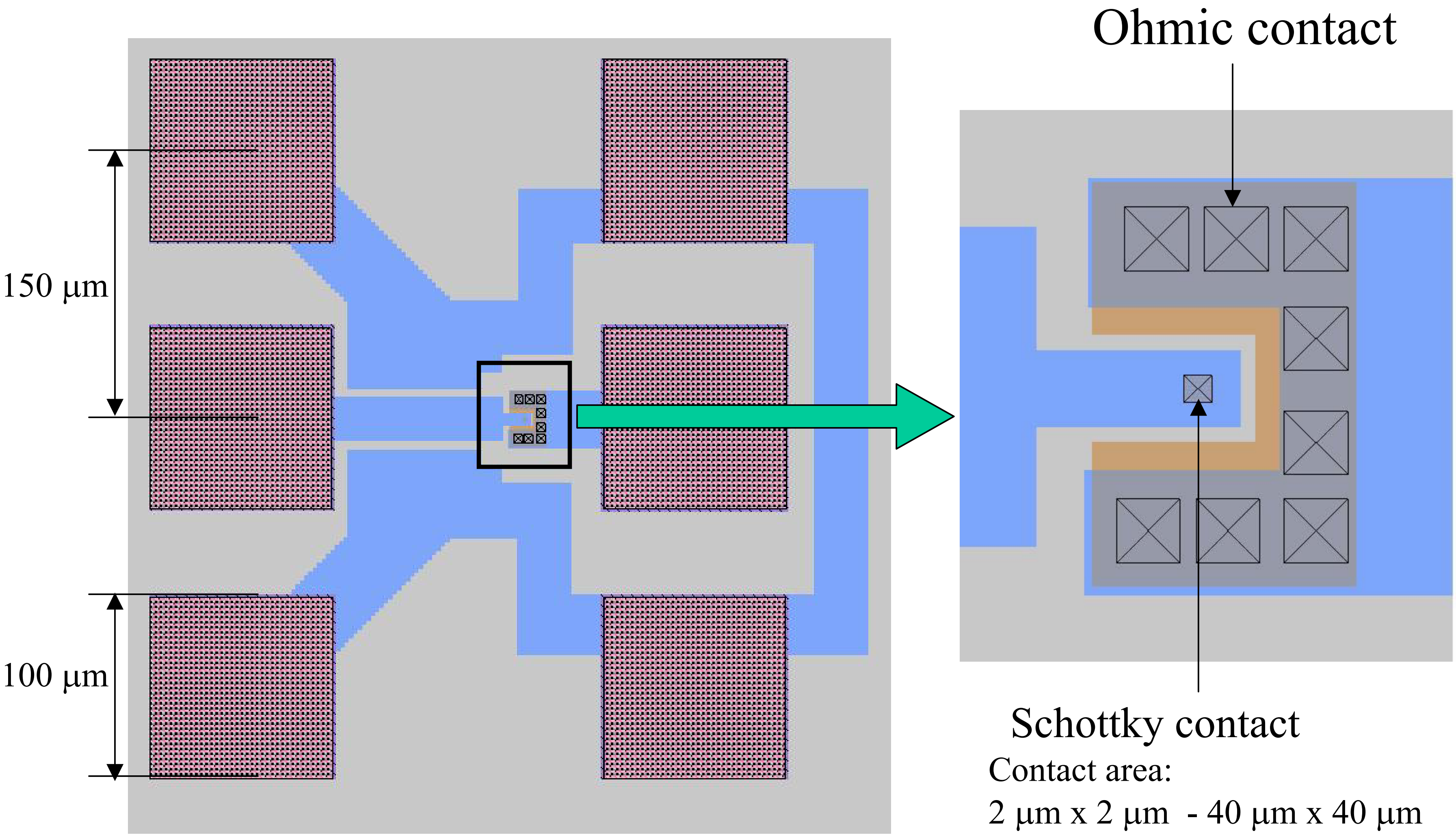


Vout vs. RF power sweep

Schottky diodes with capacitor load and MOSFET amp for amplifying small output signal

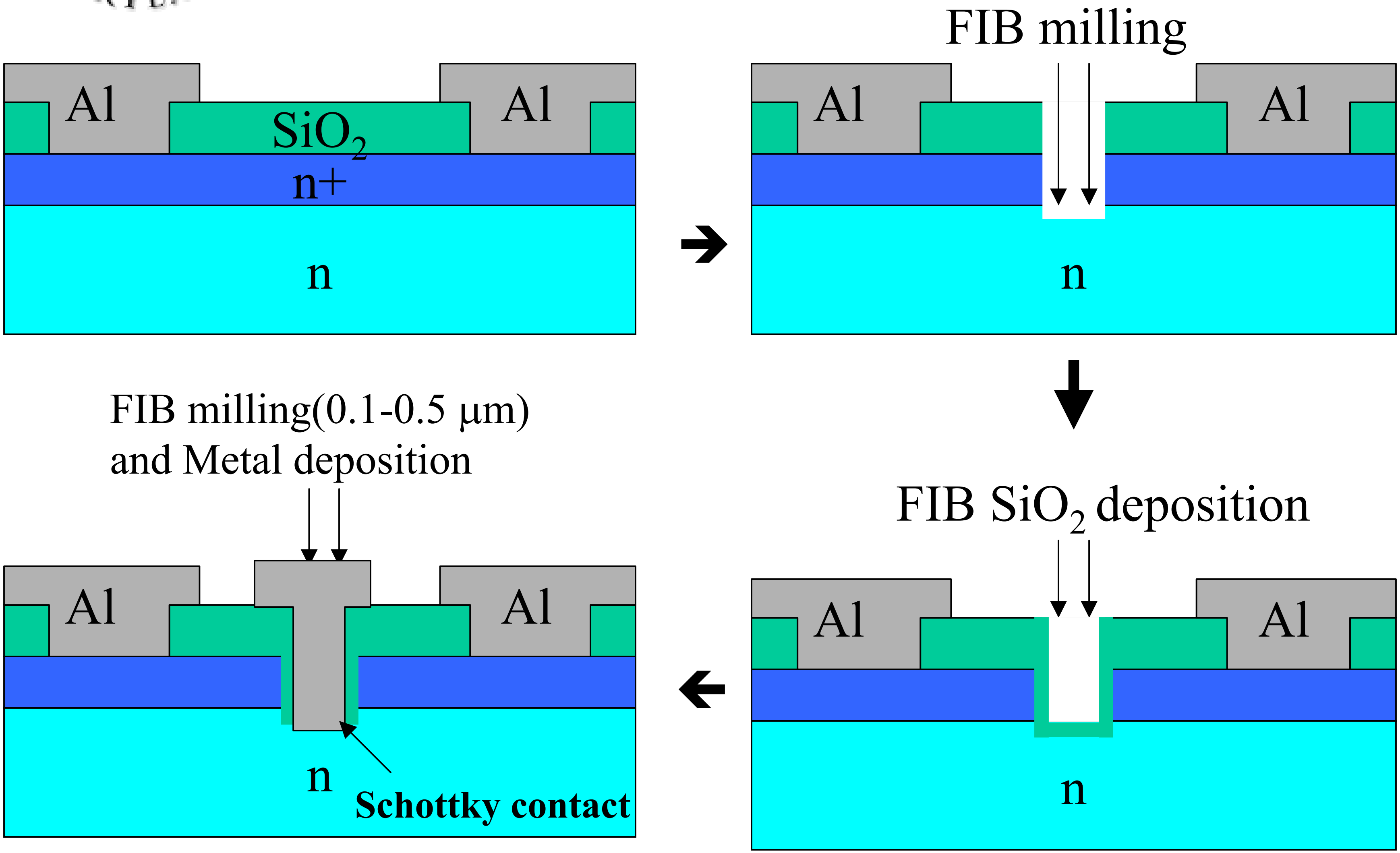


One Schottky diode



Contact area:
2 µm x 2 µm - 40 µm x 40 µm

Fabricating Schottky diode by FIB (Future work)



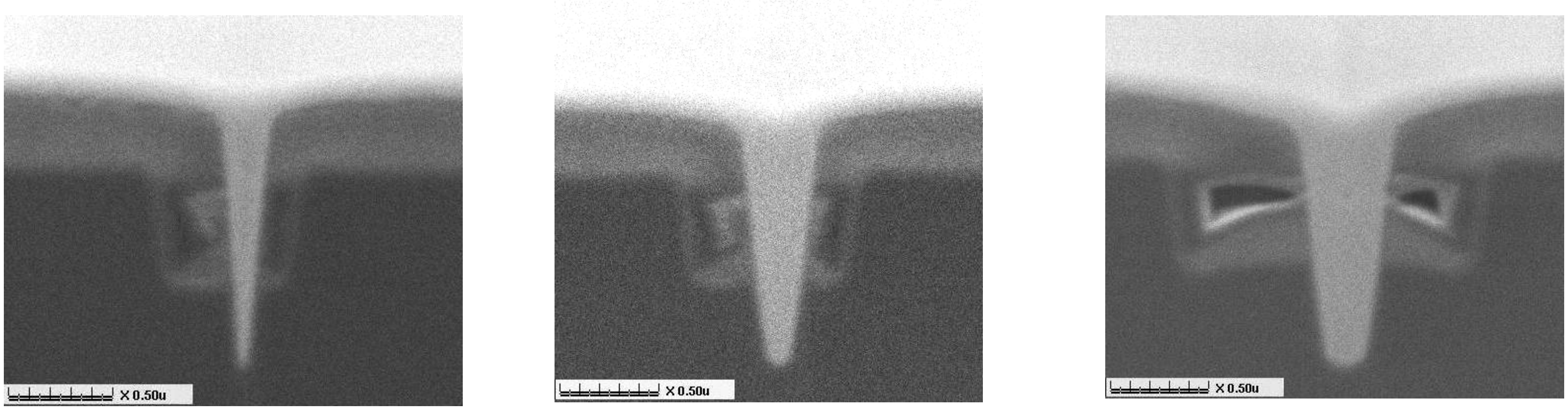
FIB milling

FIB SiO_2 deposition

FIB milling(0.1-0.5 µm)
and Metal deposition

Schottky contact

FIB Tungsten Vias
Through FIB Deposited Oxide Plugs



500nm

Summary

- Schottky diodes on n-epi and n+ substrate were fabricated and tested
- CMOS process Schottky diodes were designed, fabricated and tested with RF radiation up to 12.5GHz (50X higher than previous CMOS result) and by direct injection up to 20GHz
- Schottky diodes were fabricated by FIB techniques and tested up to 17.5 GHz
- Various Schottky diodes have been designed and submitted to MOSIS for standard CMOS processing
- Paper will be presented at the 2003 International Semiconductor Device Research Symp. in DC

Future work

- MOSIS chips now being built will be tested by RF radiation and direct injection
- Post processing MOSIS chips for FIB diodes
- Diodes with in-situ amplifiers on chip
- Diodes with built in DC bias will be designed for MOSIS and built
- Diodes will be incorporated into test chips designed by colleagues to verify various RF propagation models

Understand what limits frequency
& push toward 100GHz without MBE