INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

Design, Fabrication, and Testing of On Chip Microwave Pulse Power Detectors

Woochul Jeon & John Melngailis

*** RF Measurement & design: Todd Firestone & John Rodgers**

•IC circuit design: Robert Newcomb

University of Maryland

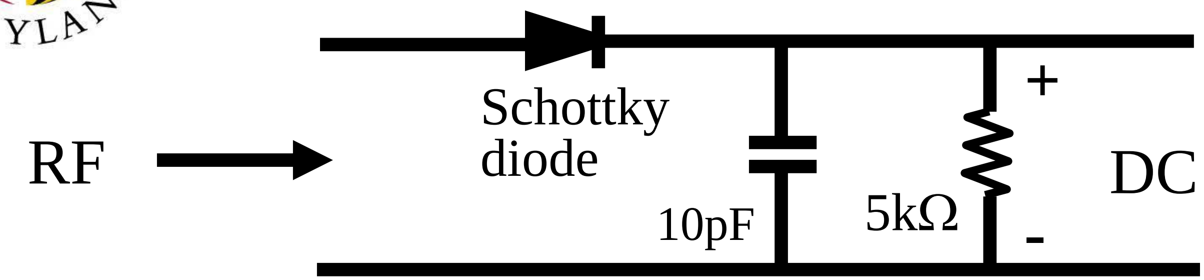
Motivation:

-- incident hostile RF radiation on electronics can cause most harm at the chip level

-- a way of measuring the level of the RF voltages induced on the most vulnerable sites is useful

-- conventional probing of the chip will disturb the measurement, *so build the detector into the chip*

Microwave pulse power detector

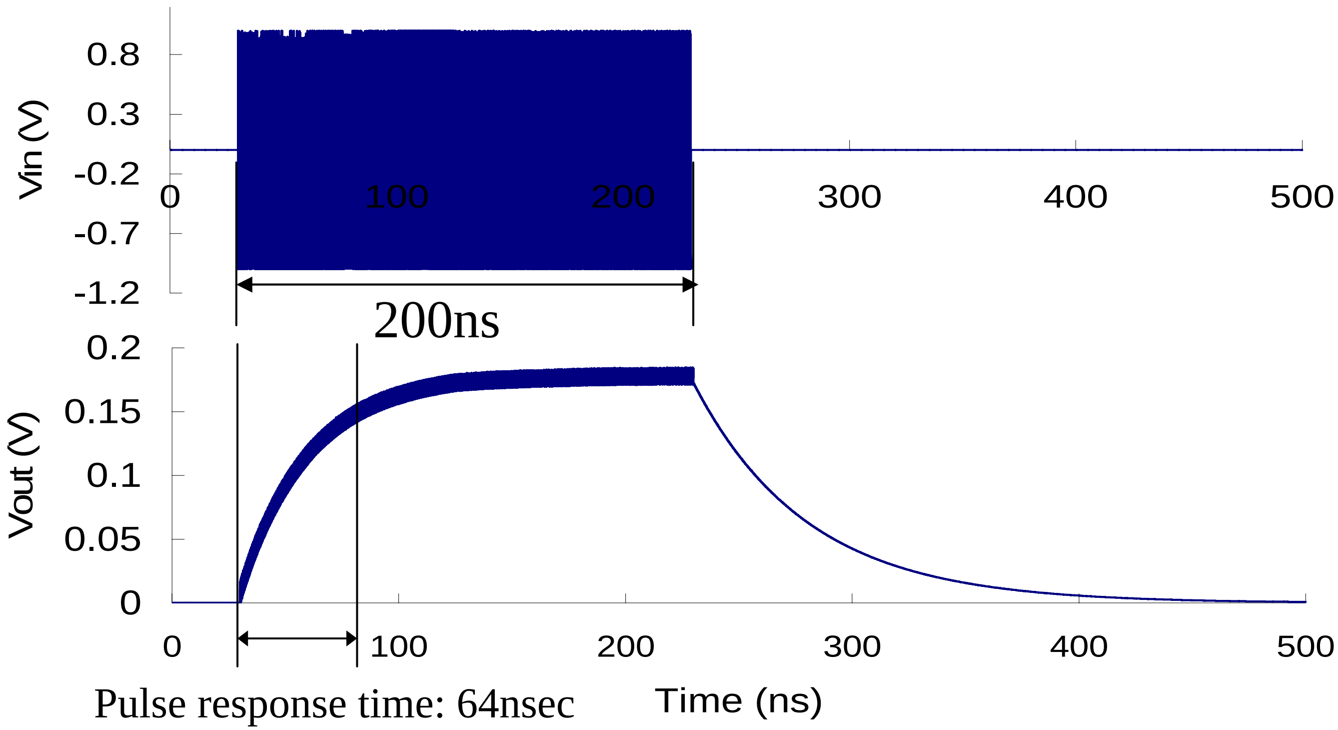


Schottky diode model:

- turn on voltage: 0.2V
- Series resistance: 214Ω
- Junction capacitance: 16fF

RF input:
5GHz,
$2V_{p\_p}$

Output

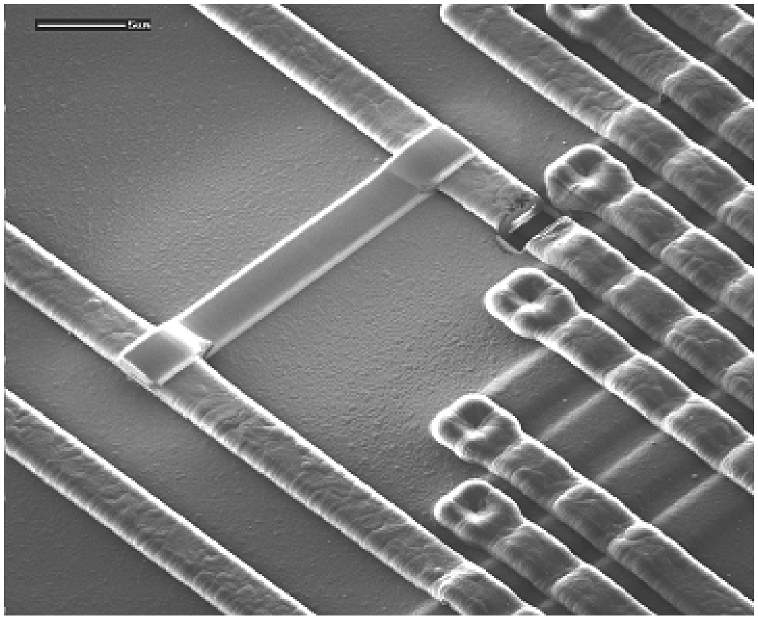


➔ RF input is rectified by the Schottky diode and stored in the capacitor.
RF pulse input is filtered to yield low frequency signal.

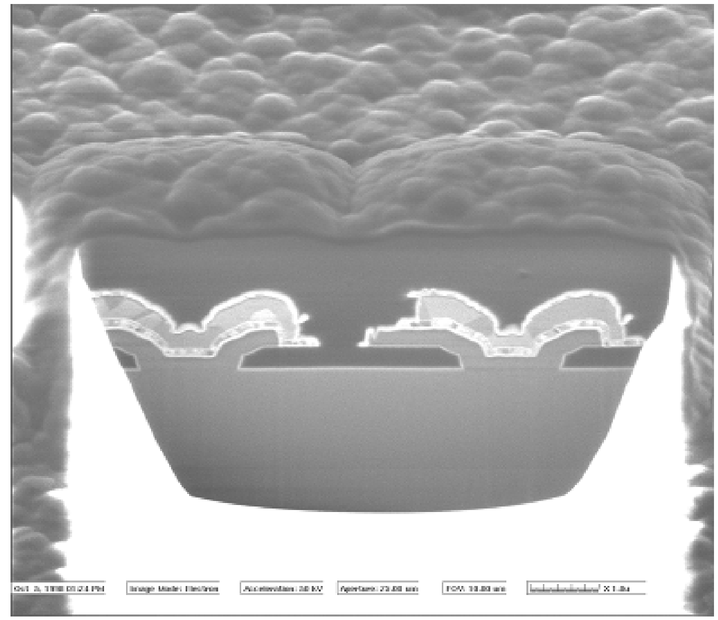
Three ways to make diode detectors on chips

- Post CMOS fabricated Schottky diode (FIB)
- CMOS process Schottky diode
- MOSFET used as rectifier
  - half wave rectifier
  - full wave rectifier

Focused Ion Beam milling and deposition
(Post-CMOS fabrication, access to silicon)



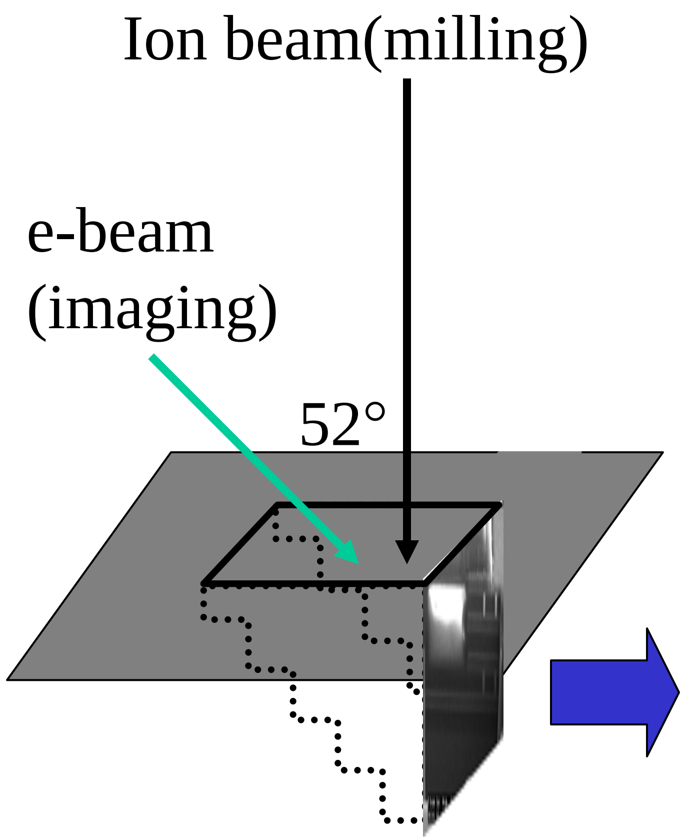
Circuit Rewiring: Cut and Jumper

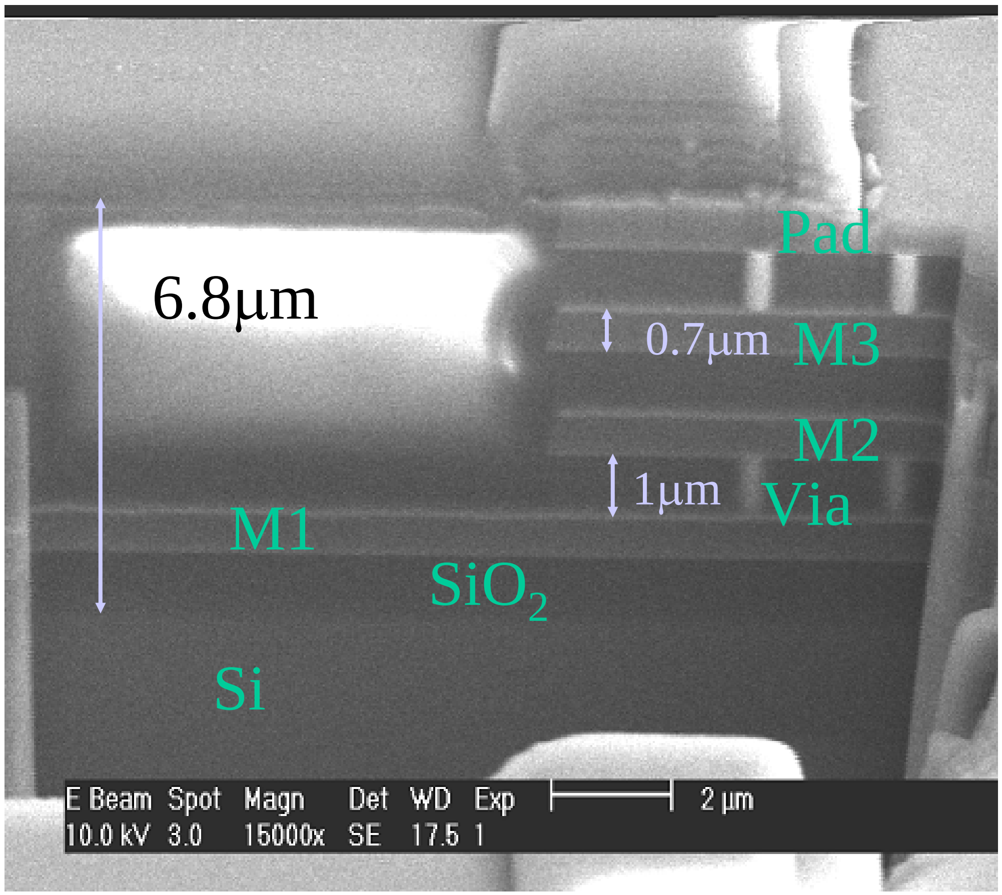


FIB-Milled Circuit Cross Section

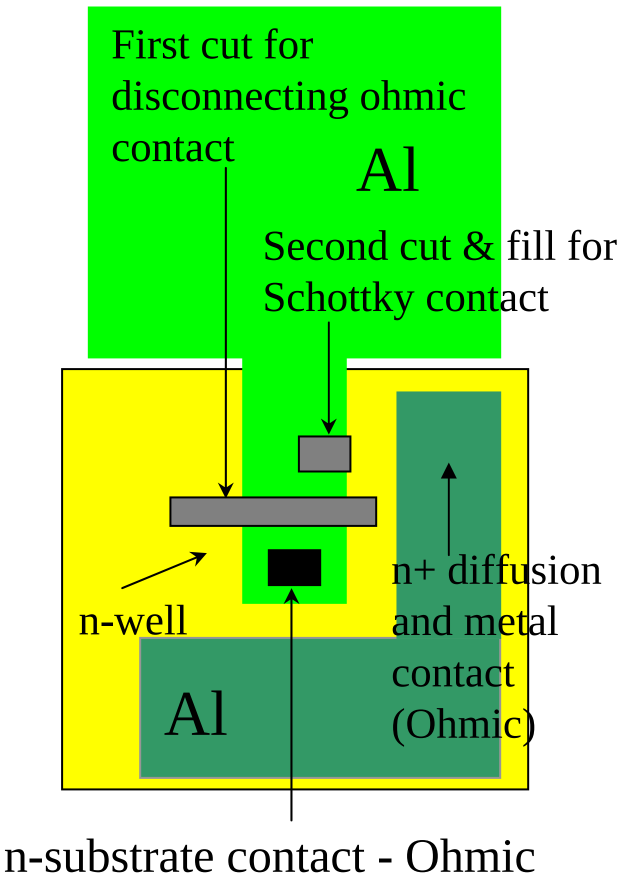
- Maskless fabrication of devices by milling or depositing materials at any location
- Possible 3D fabrication by tilting the sample stage

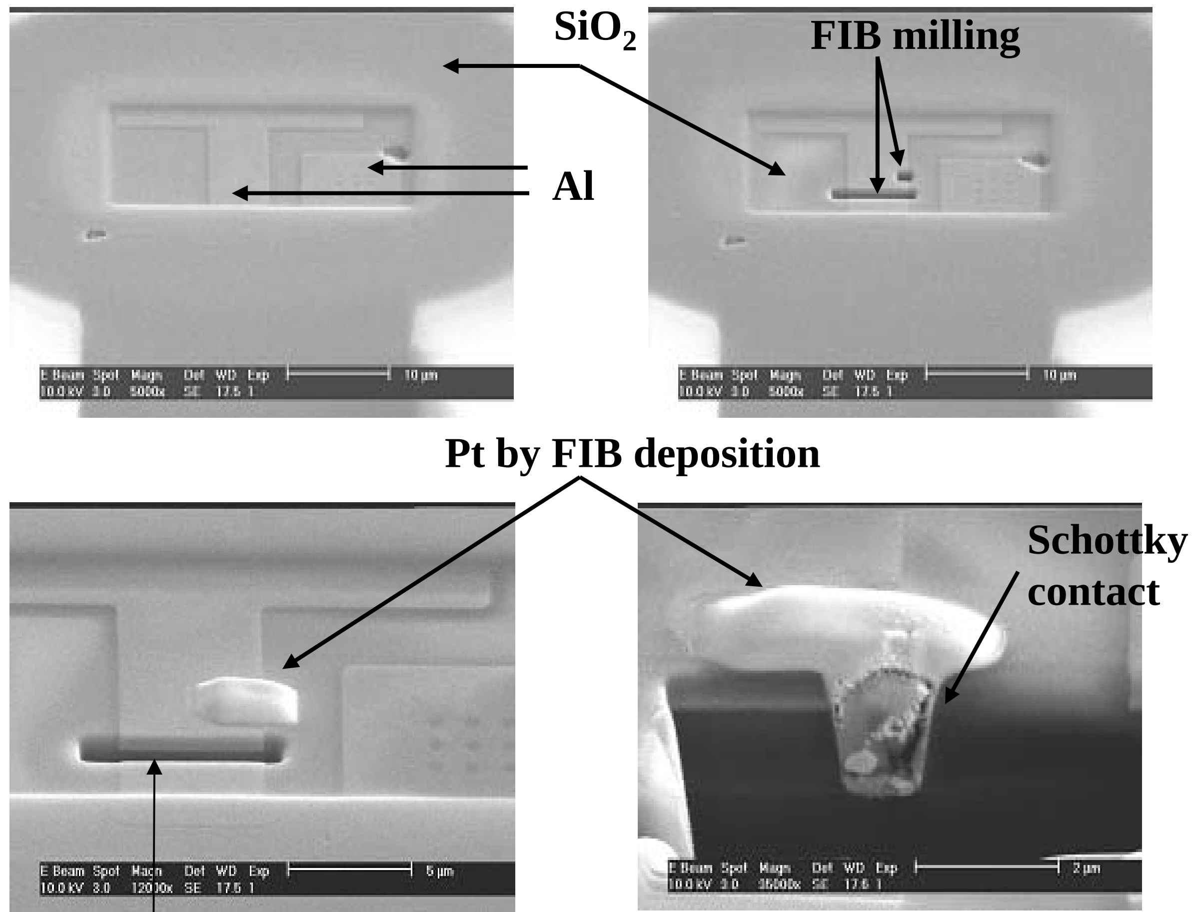
Cross section a CMOS chip





Fabrication of Schottky diode by FIB on a CMOS chip, etched down to metal-1





• cut to disconnect ohmic contact

• Cross section of burned out device after applying 8V of forward bias voltage

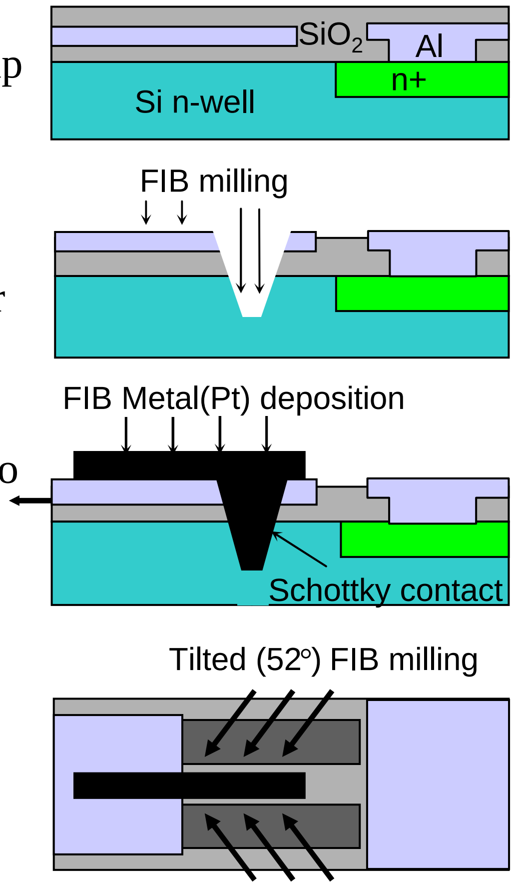
Fabrication of Bridge shaped Schottky diode by FIB on a CMOS chip

Start with a CMOS chip

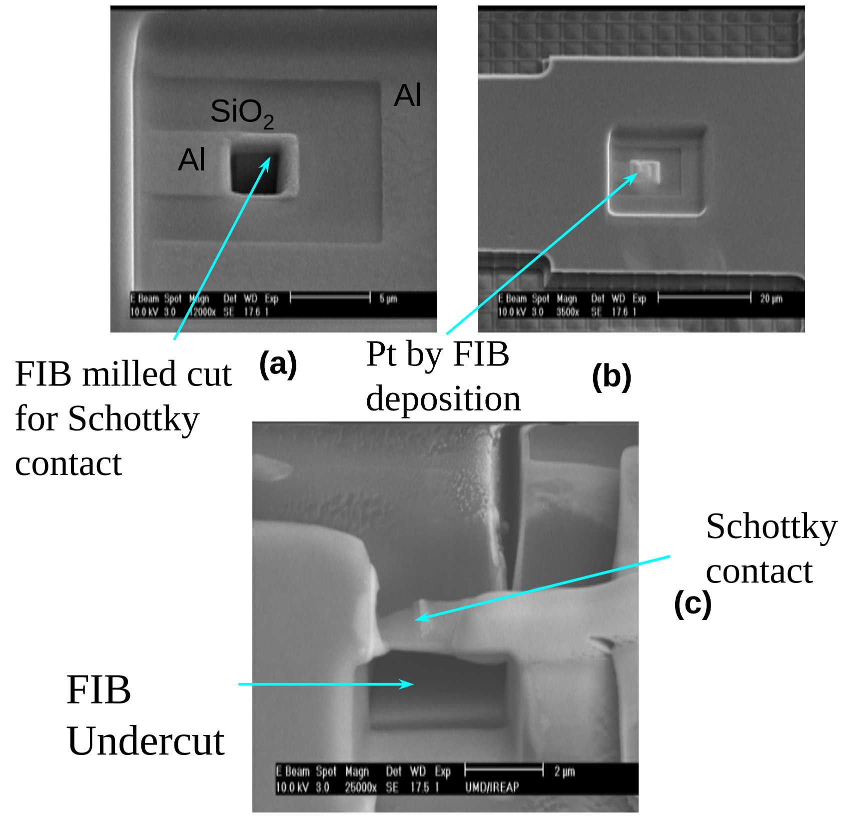
Mill SiO2 to expose metal and Si layer for contacting to pad

Metal layer connected to the pad for directly injecting RF signal

52° tilted FIB milling from two sides for undercut



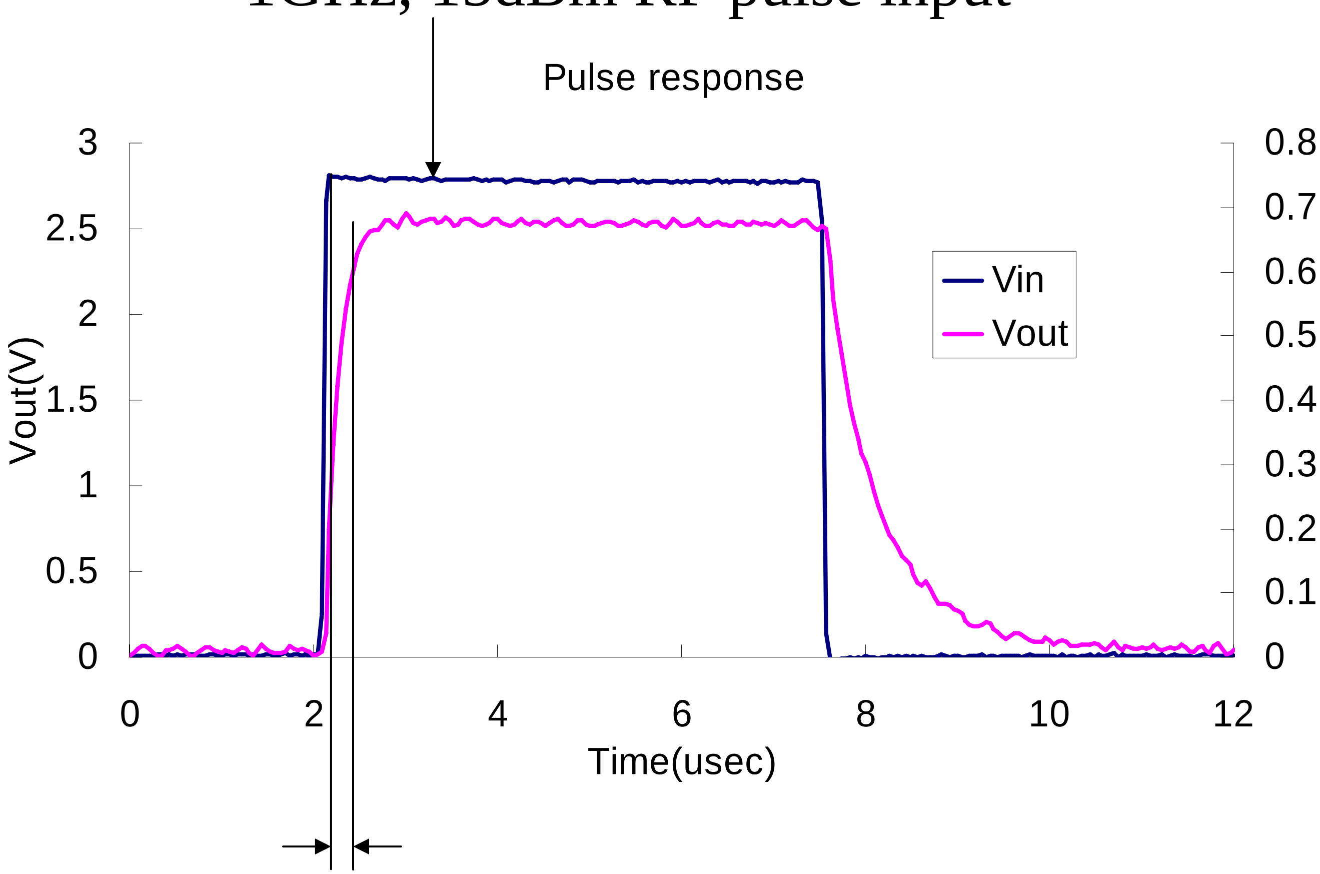
FIB Schottky diode fabrication



SEM image of a FIB processed diode
(a) Milling silicon and Platinum deposition,
(b) Cross section of the fabricated device:
(c) Undercut by tilted FIB to minimize contact area

RF pulse response of Bridge shaped FIB Schottky diode

1GHz, 15dBm RF pulse input



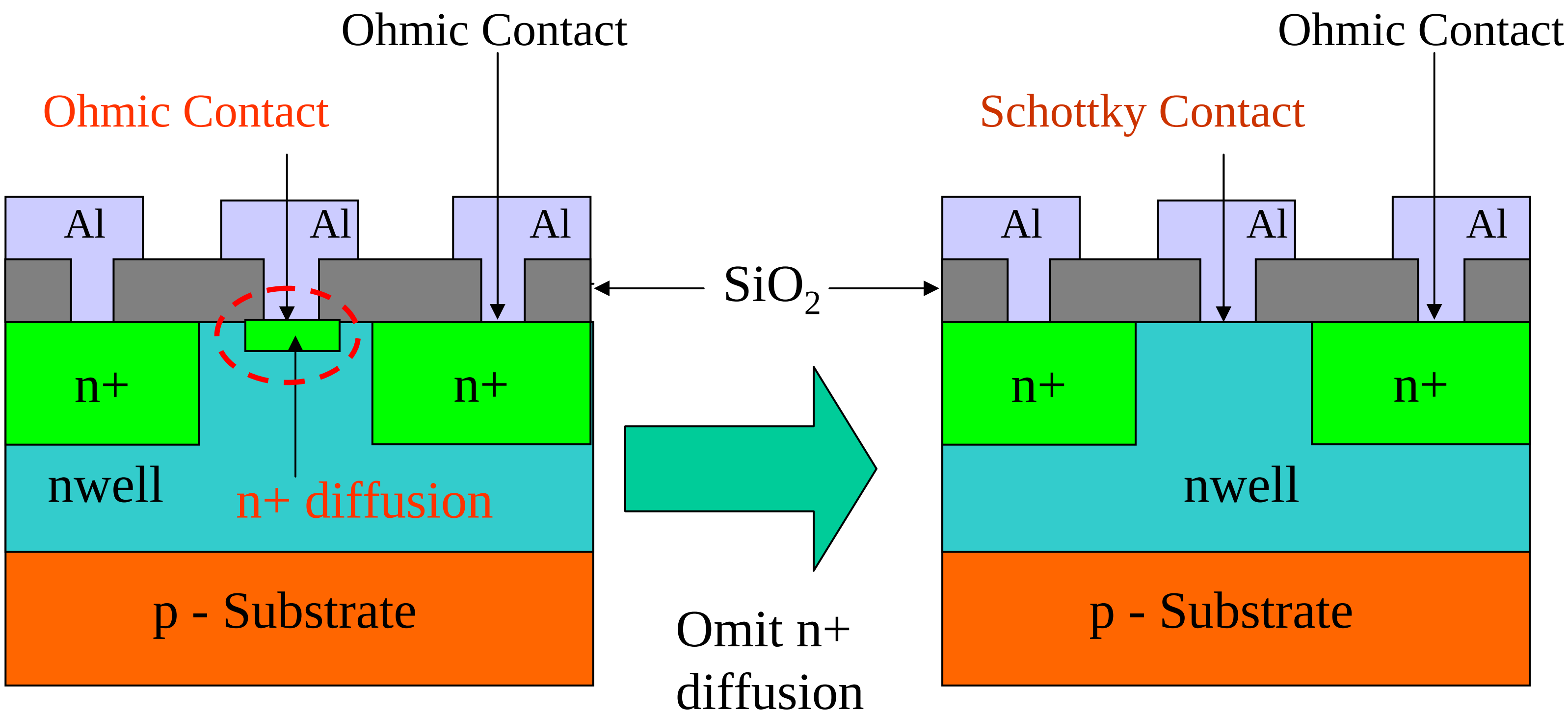
Pulse response time: 170ns

CMOS Schottky diodes

- Standard CMOS process does not allow a Schottky contact

➔Modification required

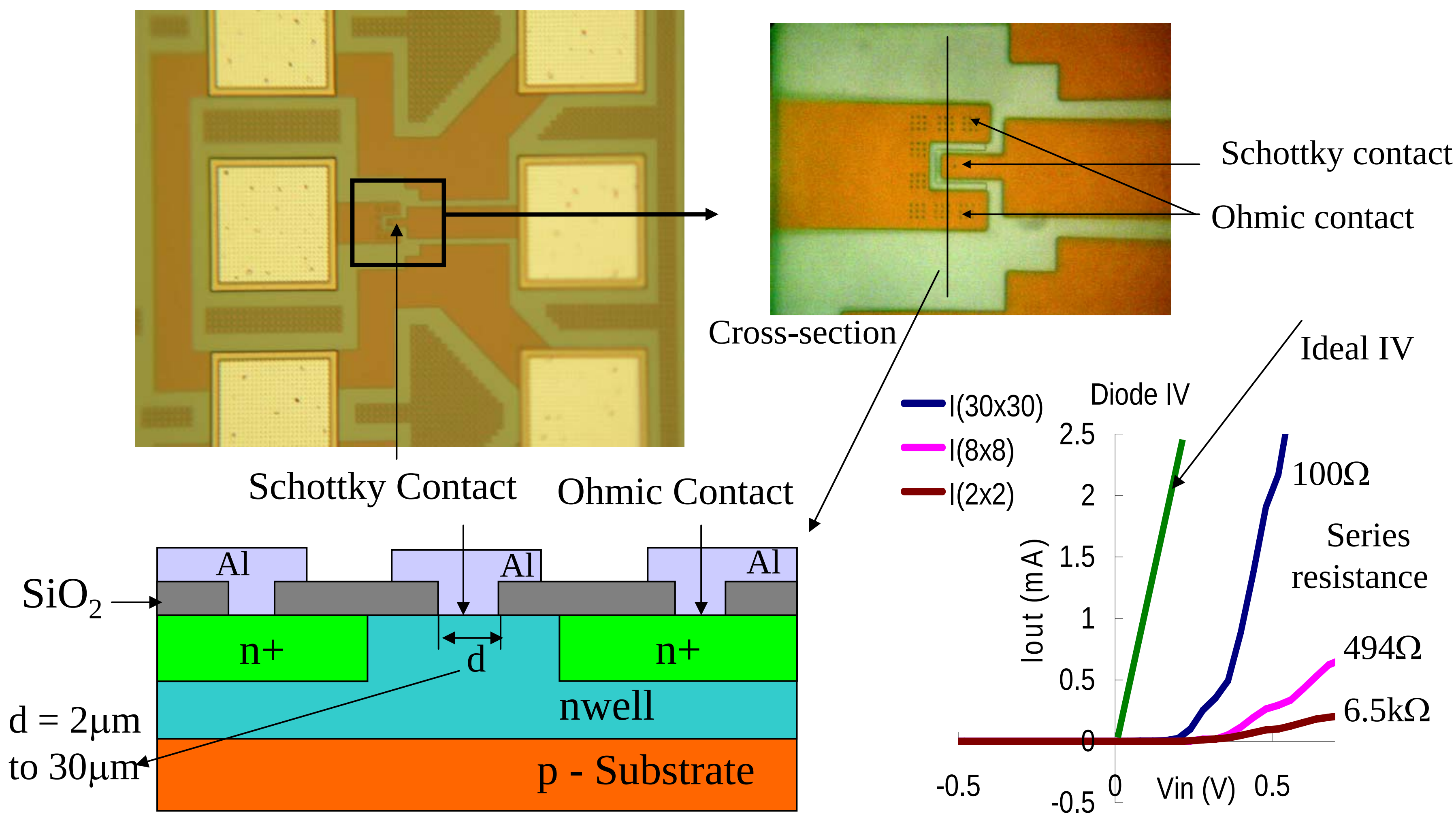
➔Skip n+ diffusion in metal to nwell contact area



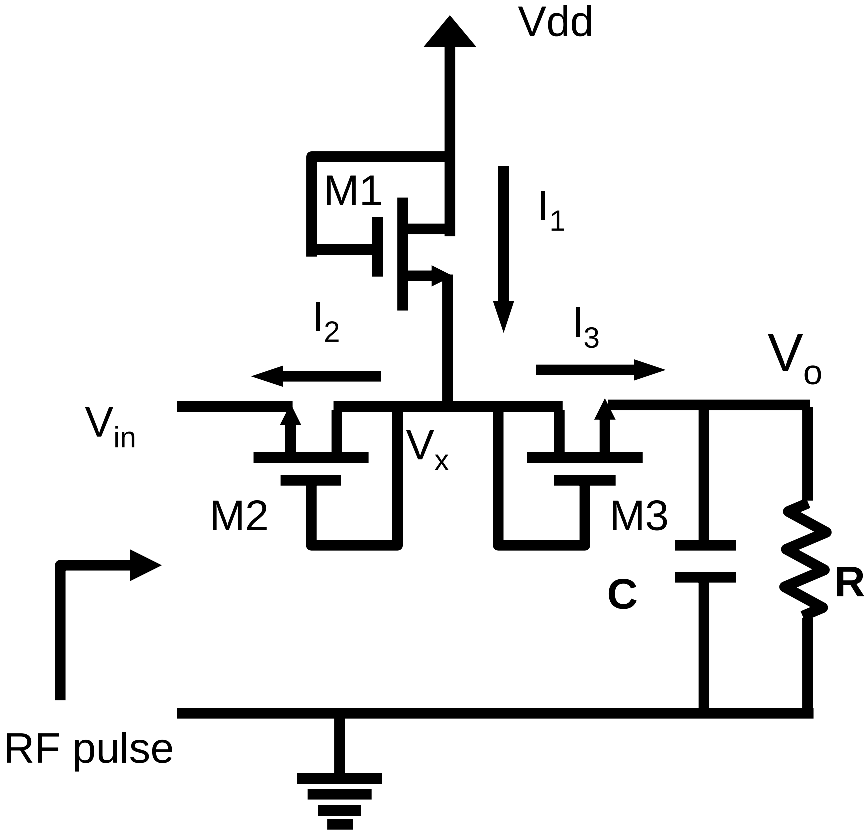
nwell-metal contact in Standard CMOS process

Modified nwell-metal contact (Schottky contact)

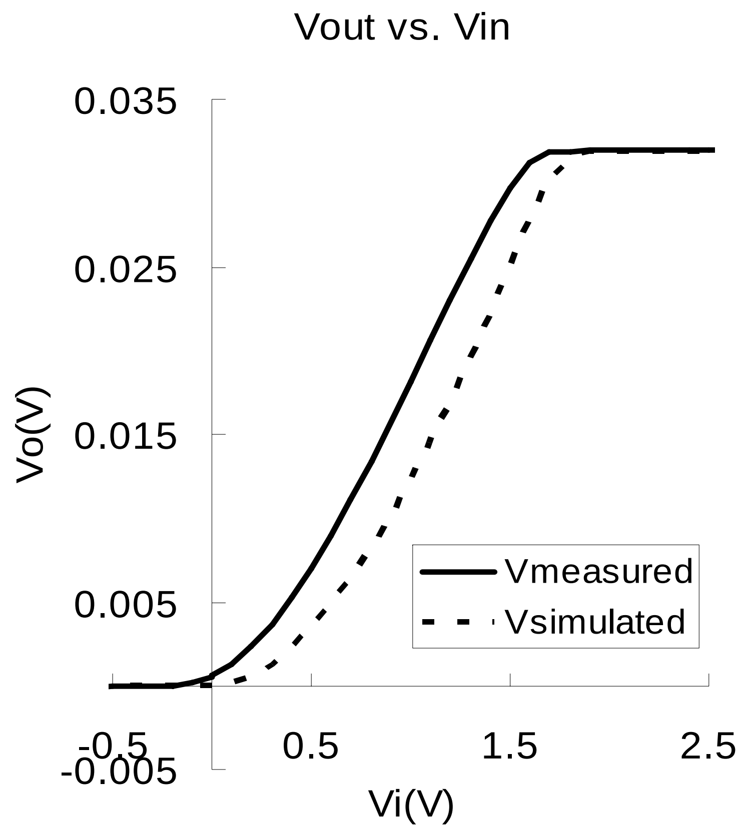
CMOS Schottky diodes



Alternative CMOS design (MOSFET diode)



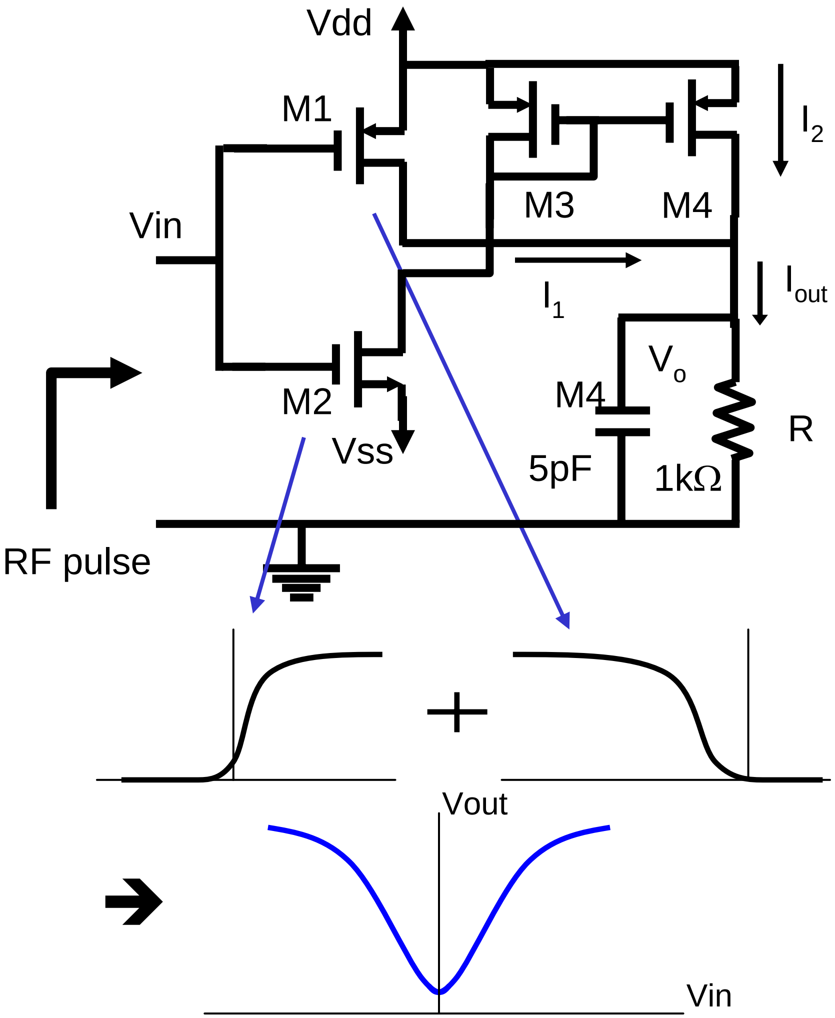
MOSFET diode power detector circuit

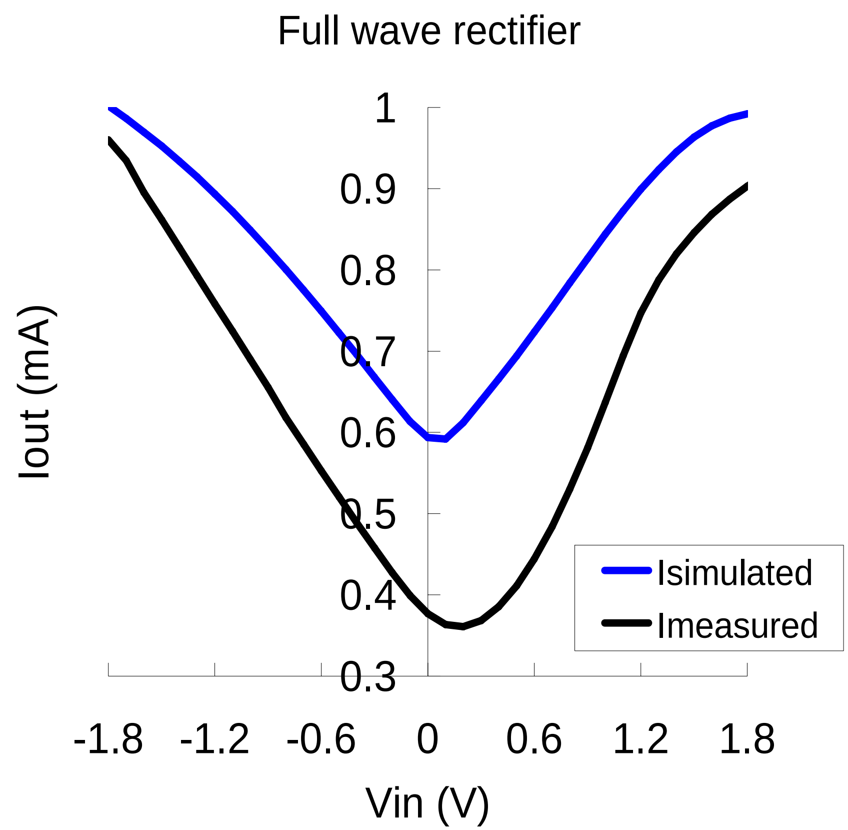


DC Simulation and measured result

Measured result: turn on voltage shift to –0.1V

MOSFET detector circuit
Full-wave rectifier circuit

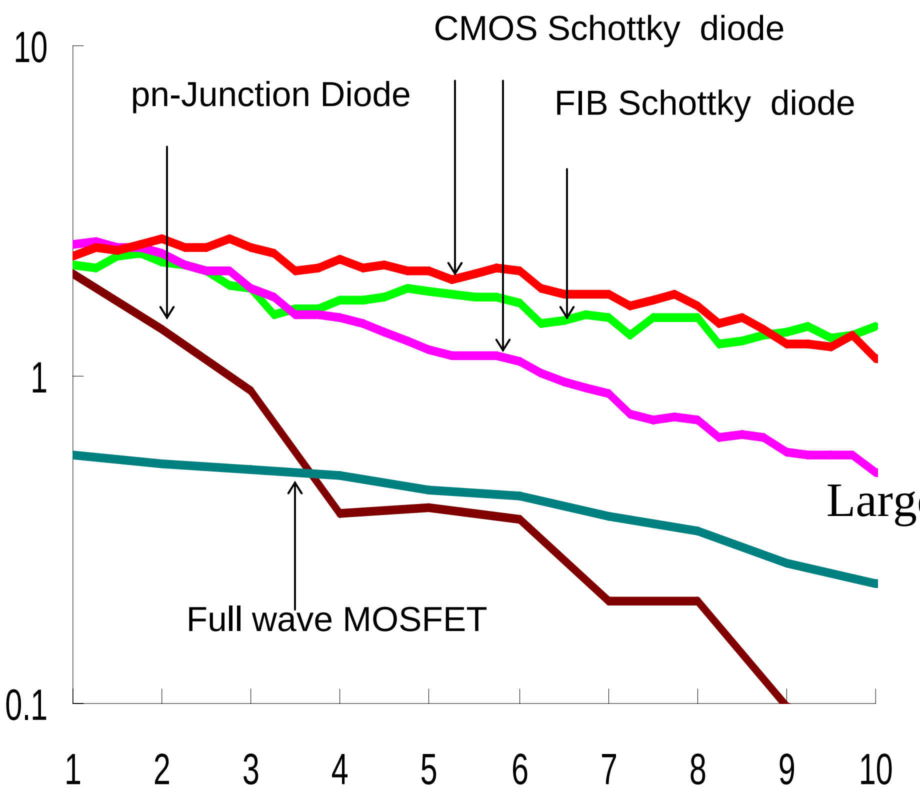




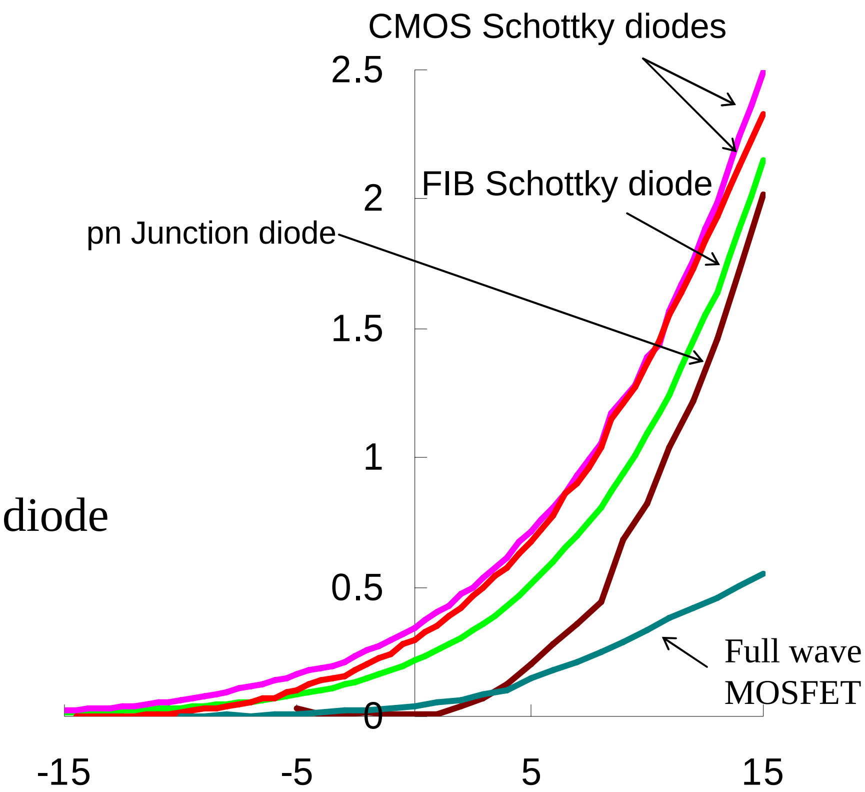
DC Simulation and measured result

Measured result: turn on voltage shift to 0.2V

Measured result (Comparison)



Large diode



Frequency sweep (1GHz to 10GHz) at 15dBm

Power sweep (-15dBm to 15dBm) at 1GHz

Comparison table

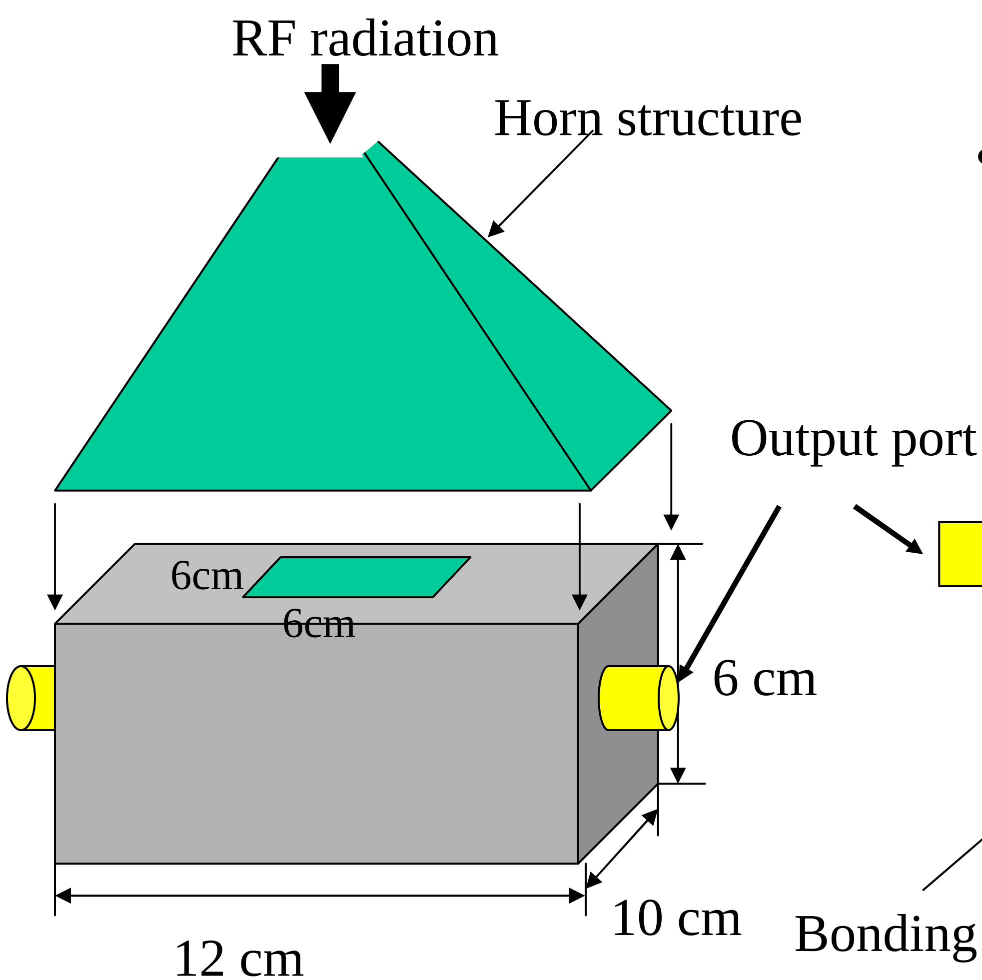
	CMOS diode		FIB diode			MOSFET detector		Full wave MOSFET	pn Junction diode
	n-type 92μm^2	n-type 1.4μm^2	p-type 4μm2	n-type 15μm^2	Bridge 1μm^2	150kΩ Load	1kΩ Load		
Pulse response time (sec)	820n	776n	192n	6 μ	170n	200n	**56n**	101n	16μ
Frequency response (Vout at 1GHz / Vout at 10GHz)	4.93	**2.05**	4.91	3.14	3.97	9.59	4.43	2.44	27.4
Dynamic range (dBm)	**36**	34.5	16.5	25.5	26	23	25	25	12
Sensitivity (dBm) (smallest possible detection)	**-21**	-19.5	-1	-20.5	-11	-18	-10	-10	3

Best for sensitivity & dynamic range

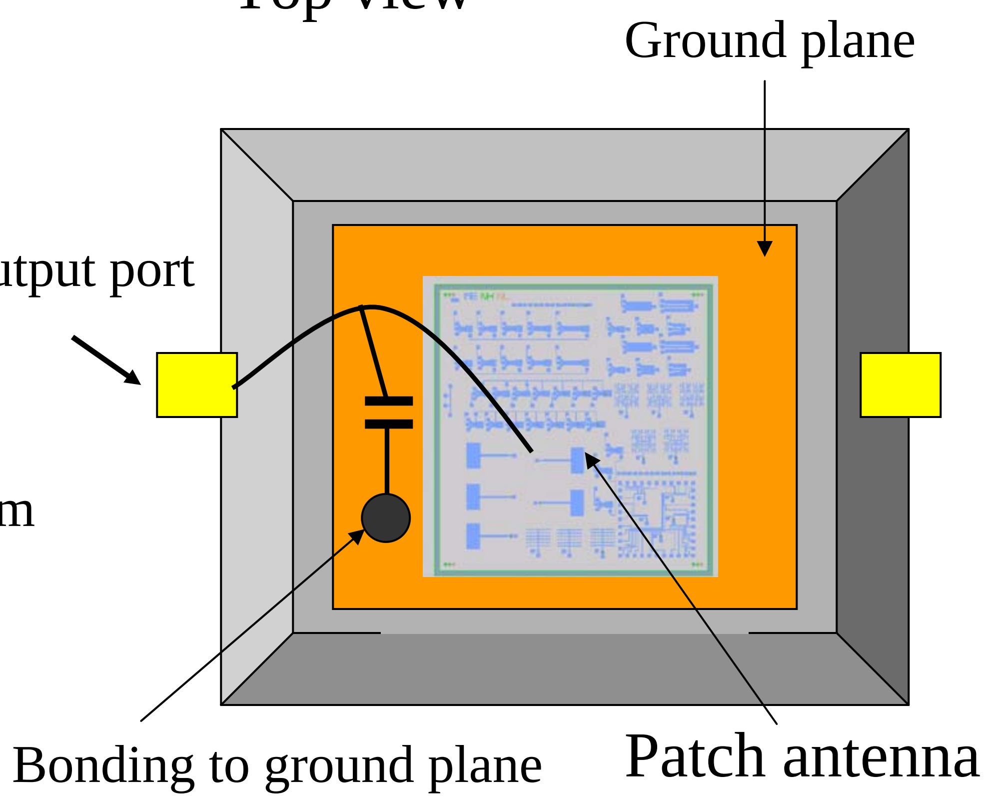
Best for short burst

RF radiation test on a patch antenna structure

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

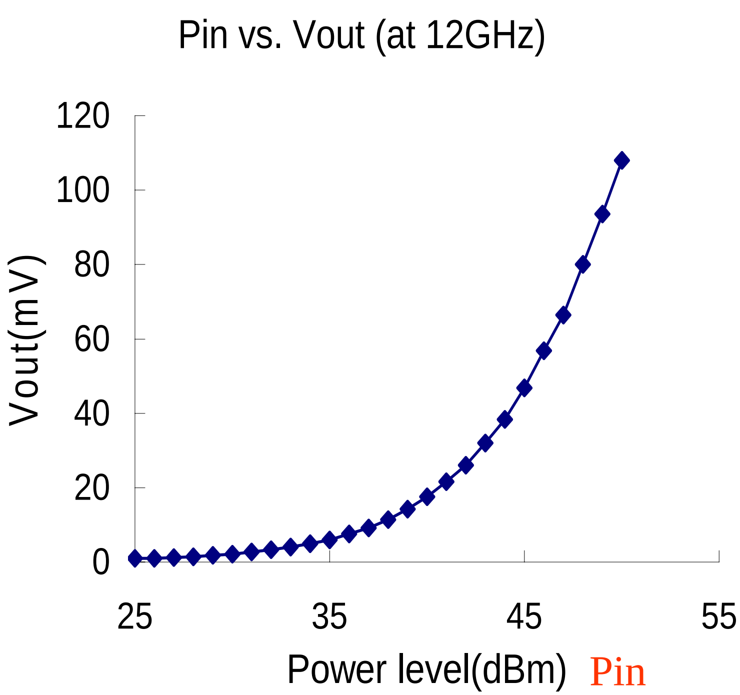


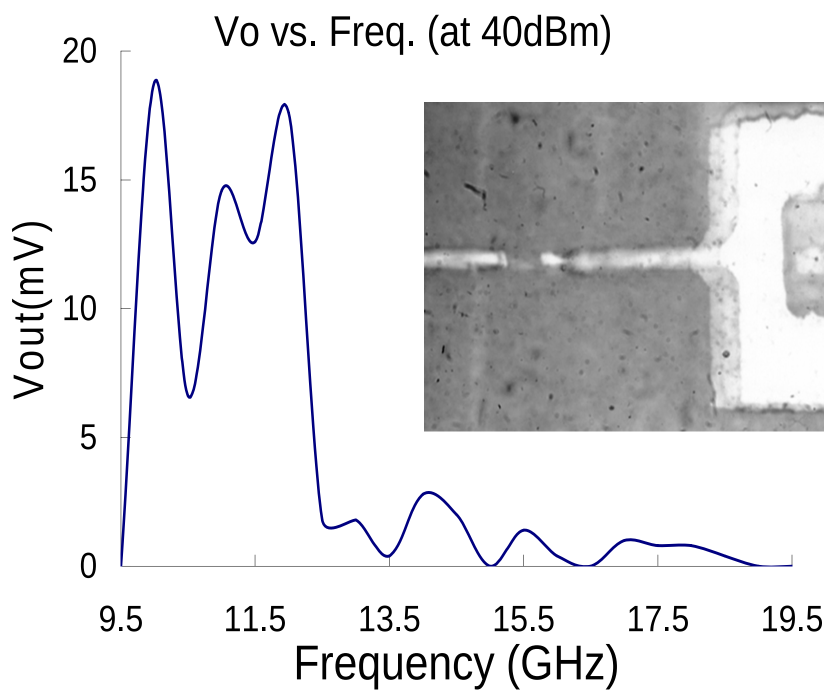
- Top view



RF radiation test result

(Illustration of applications)



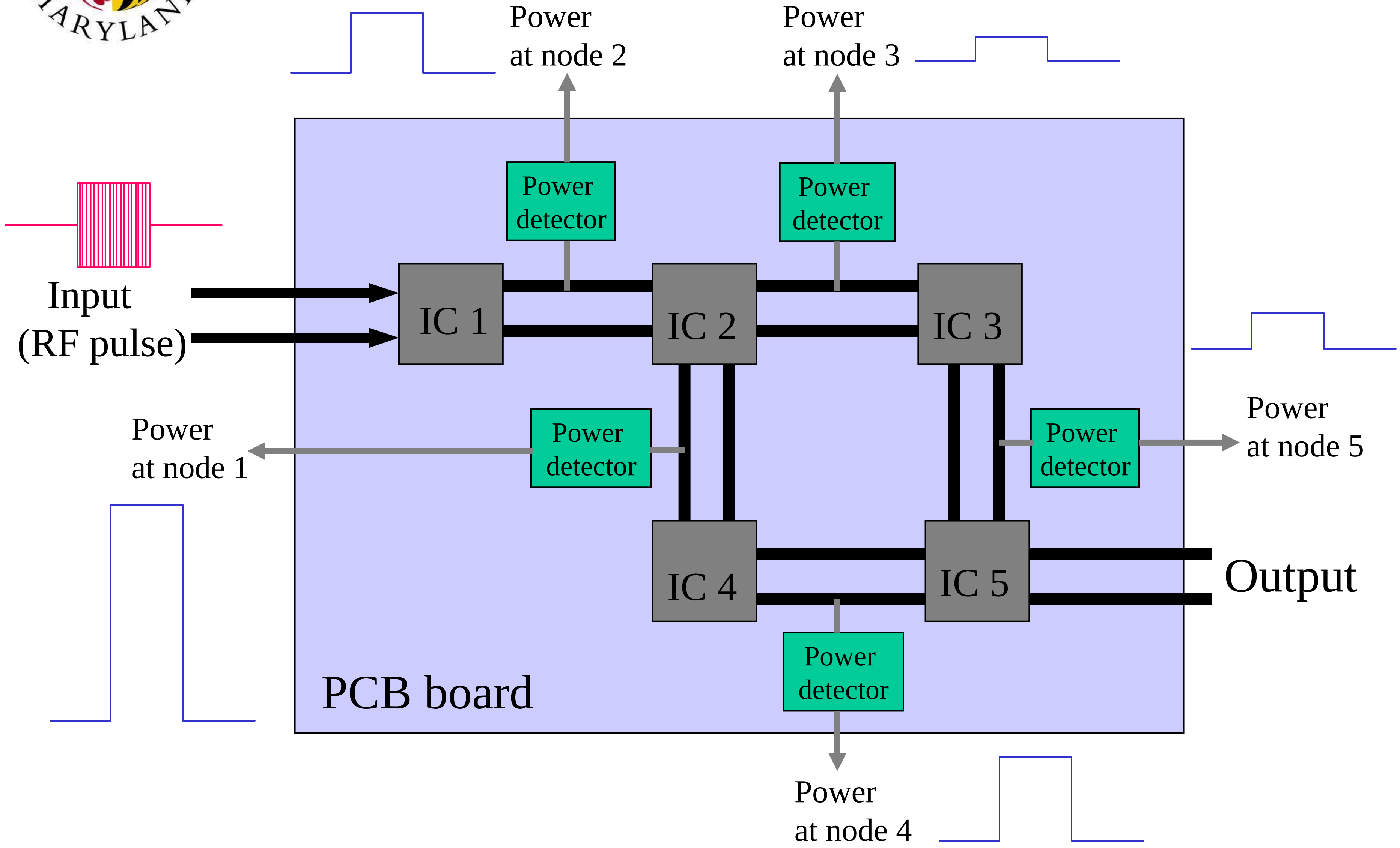


➔Working in the square law region, (Power level: output of the RF source)

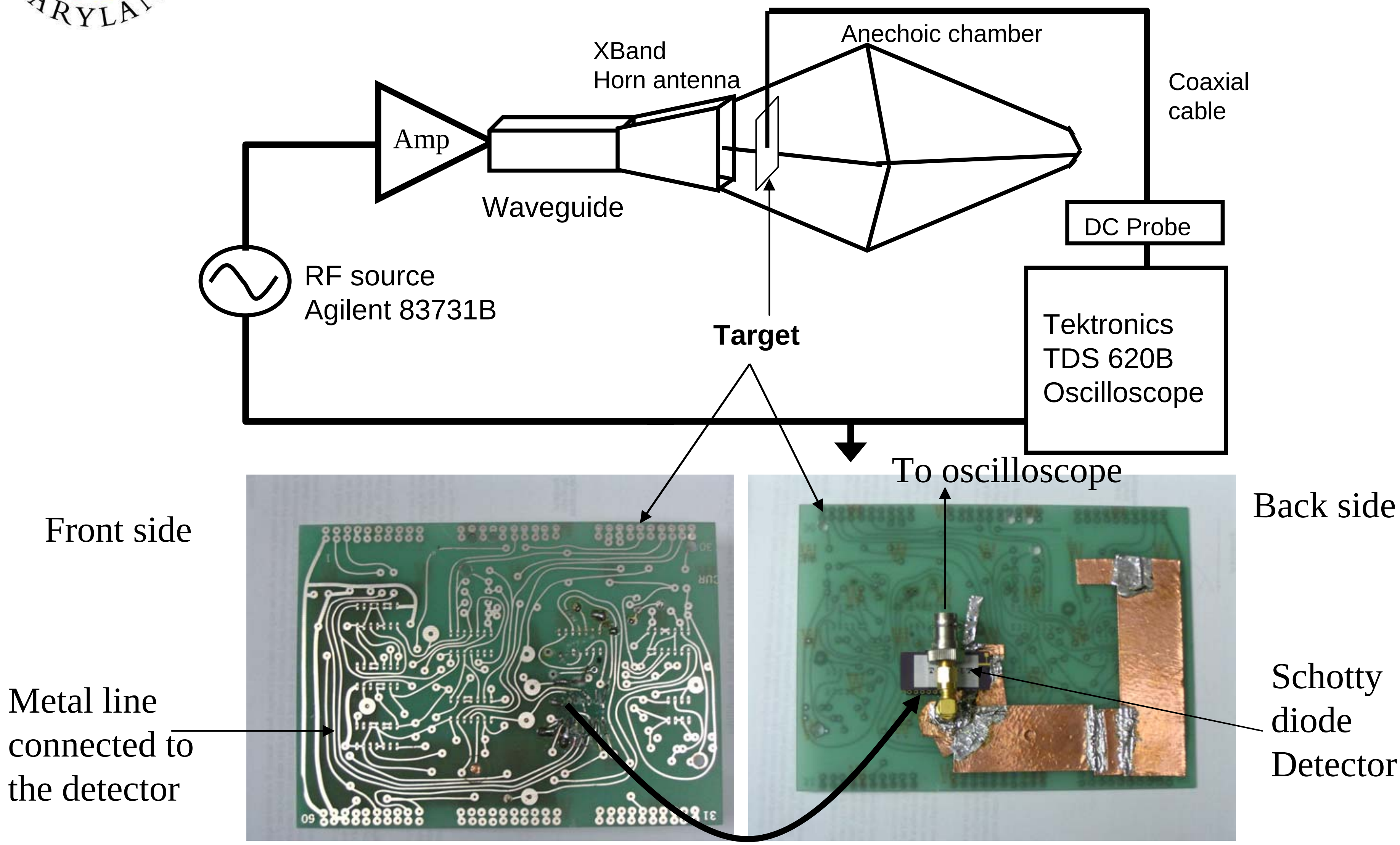
➔ Power density = $Pin \times \frac{6 \times 6cm^2}{15 \times 10cm^2} \times \frac{1}{15 \times 10cm^2} = 1.6 \times 10^{-3} Pin / cm^2$

→ Power on a patch antenna (1500x750 μm^2) ≈ Pin – 47dBm

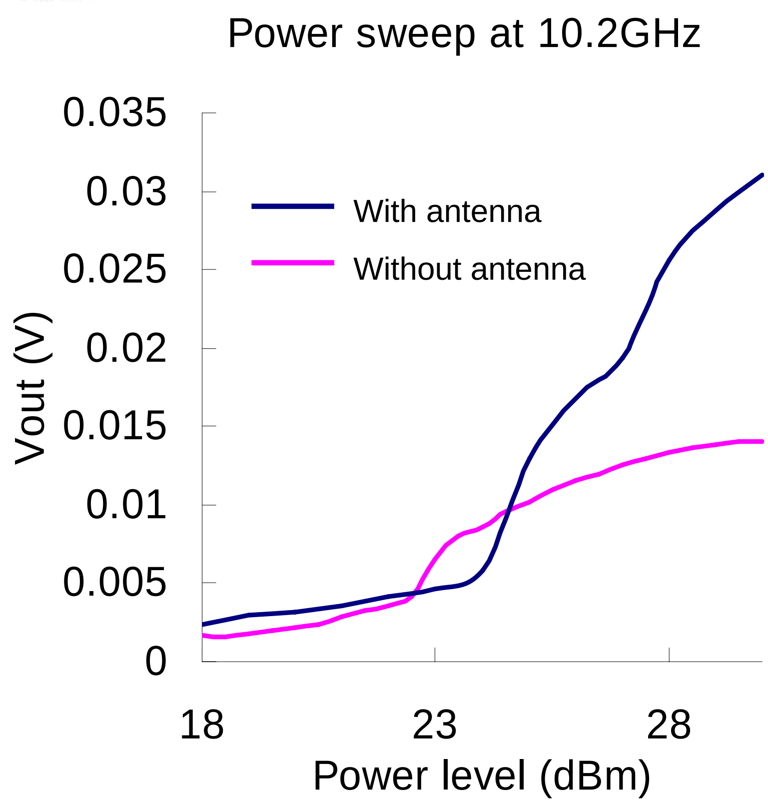
Detecting RF level at a PCB board

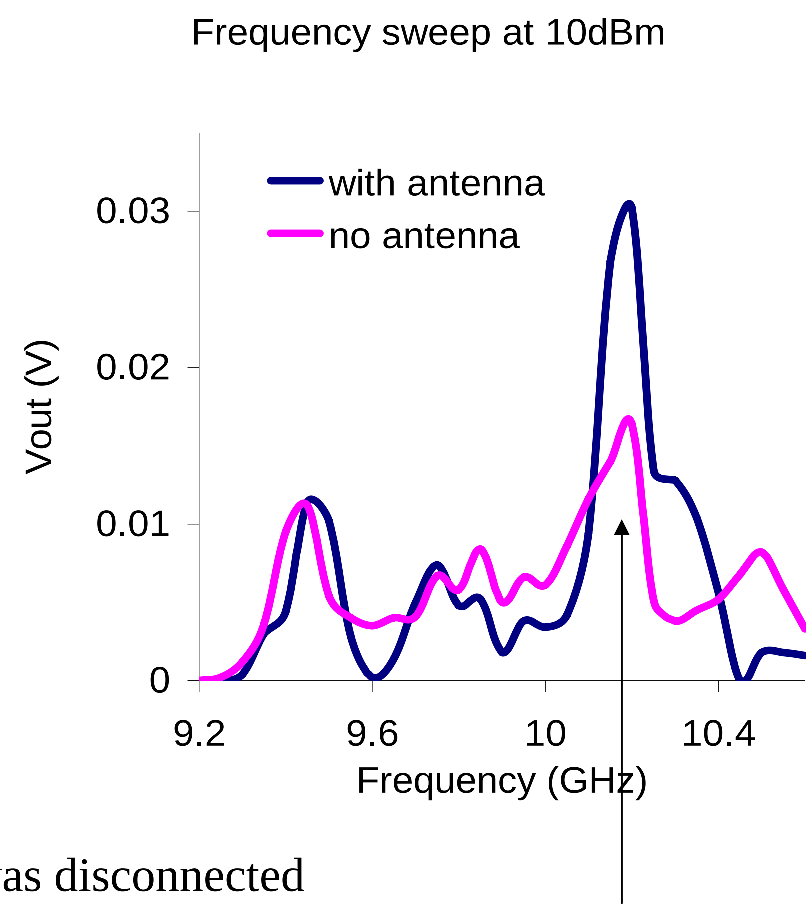


RF pulse Radiation test (x-band)
-Detecting RF level at a PCB board



RF pulse Radiation test
-Measured result





- ➔ After measurement, antenna structure was disconnected
- ➔ Similar result for with or without antenna connection except around 10.2GHz
- ➔ The metal line structure is tuned at 10.2GHz pulse signal

Summary

- fabricated on-chip microwave pulse power detectors
  - FIB Schottky diodes as a post-CMOS process
  - Schottky diodes in modified CMOS process
  - MOSFET power detector circuits

- tested and evaluated diode RF detectors
  - using probes
  - RF incident on chip
  - RF incident on circuit board with chip

Future work & Challenge

- fabricate chips with built-in diode detectors and built in signal processing, to substitute for chips at vulnerable sites during tests

Synergistic activity:

- harvesting of RF power for passive devices

- RFID tags

- RFID tags with built-in sensors

(many applications: military logistics and monitoring, environmental, homeland security, medical…..)

Publications in Journals

W. Jeon, T. Firestone, J. Rodgers, and J. Melngailis, “Design and fabrication of Schottky diode, on-chip RF power detector”, Solid state electronics, Vol. 48, Iss. 10-11, pp. 2089-2093, Oct 2004

W. Jeon, T. Firestone, J. Rodgers, J. Melngailis, “On-chip RF pulse power detector using FIB as a post-CMOS fabrication process”, Electromagnetics, Vol. 26, Num 1, pp. 103-109, Jan 2006

W. Jeon and J. Melngailis, “CMOS and post-CMOS on-chip microwave pulse power detectors”, Solid state electronics, in press

Conferences

W. Jeon, T. Firestone, J. Rodgers, and J. Melngailis, "Design and fabrication of Schottky diode, on-hip RF power detector", Proc., 2003 ISDRS, pp. 294-295, Washington DC, Dec. 2003

W. Jeon and J. Melngailis, "CMOS & Post CMOS Fabrication of on Chip Microwave Pulse Power Detectors", Proc., ISAP2005, Vol. 1, pp 221-224, Seoul, Korea, Aug. 2005

W. Jeon, T. Firestone, J. Rodgers, J. Melngailis, "CMOS/post-CMOS fabrication of on-chip Schottky diode microwave pulse power detectors", Proc., DET&E conference, Albuquerque, New Mexico, Aug. 2005

W. Jeon, J. Melngailis, and R. W. Newcomb, "CMOS passive RFID transponder with read-only memory for low cost fabrication", Proc., IEEE SOCC 05, pp. 181-184, Washington DC, Sept. 2005

W. Jeon and J. Melngailis, "CMOS&post CMOS on-chip microwave pulse power detectors" Proc., 2005 ISDRS, Washington DC, Dec. 2005

W. Jeon, J. Melngailis, and R. W. Newcomb, "CMOS Schottky diode microwave power detector fabrication, Spice modeling, and application", IEEE Intl. Work. Electronic Design, Test, & Applications (DELTA 2006), pp 17-22, Kuala Lumpur, Malaysia, Jan. 2006

W. Jeon and J. Melngailis, "On-chip CMOS microwave pulse power detectors", 2006 IEEE Power Modulator Conference abstracts, pp 64-65, Washington DC, May 2006

Related, e.g. RFID

W. Jeon, J. Melngailis, and R.W. Newcomb, "Disposable CMOS passive RFID transponder for patient monitoring", IEEE ISCAS, pp 5071-5074, Island of Kos, Greece, May 2006

M. Moskowitz and W**.** Jeon, **"**Design of Portable integrated Diode-Based Biosensor for diabetic diagnoses", World Congress on Medical physics and Biomedical engineering, Seoul, Aug. 2006, accepted

W. Jeon and J. Melngailis, "CMOS Schottky diode for photo-detector and thermal detector applications", IEEE sensors, Oct 2006, accepted

RF pulse Radiation test -Measured result

- Antenna gain: The ability to focus radio waves in a particular direction (dBi : decibels relative to isotropic)

For 0.0302V output at 10.2GHz, -2.8dBm direct injection needed

$$G_{Rx} = \frac{16 P_{Rx} \pi^2 d^2 L}{P_{Tx} G_{Tx} \lambda^2}$$

d = 1cm (distance b/w antenna and target)
G_{Tx} = 23.28 dB (Horn antenna gain)
L = 1 (system loss factor, assumed)
λ = 2.96cm (wave length)

GRx = -43.53dBi

P_{Tx} = 30dBm (Radiated power)
P_{Rx} = -2.8dBm (Received power)

Radiation

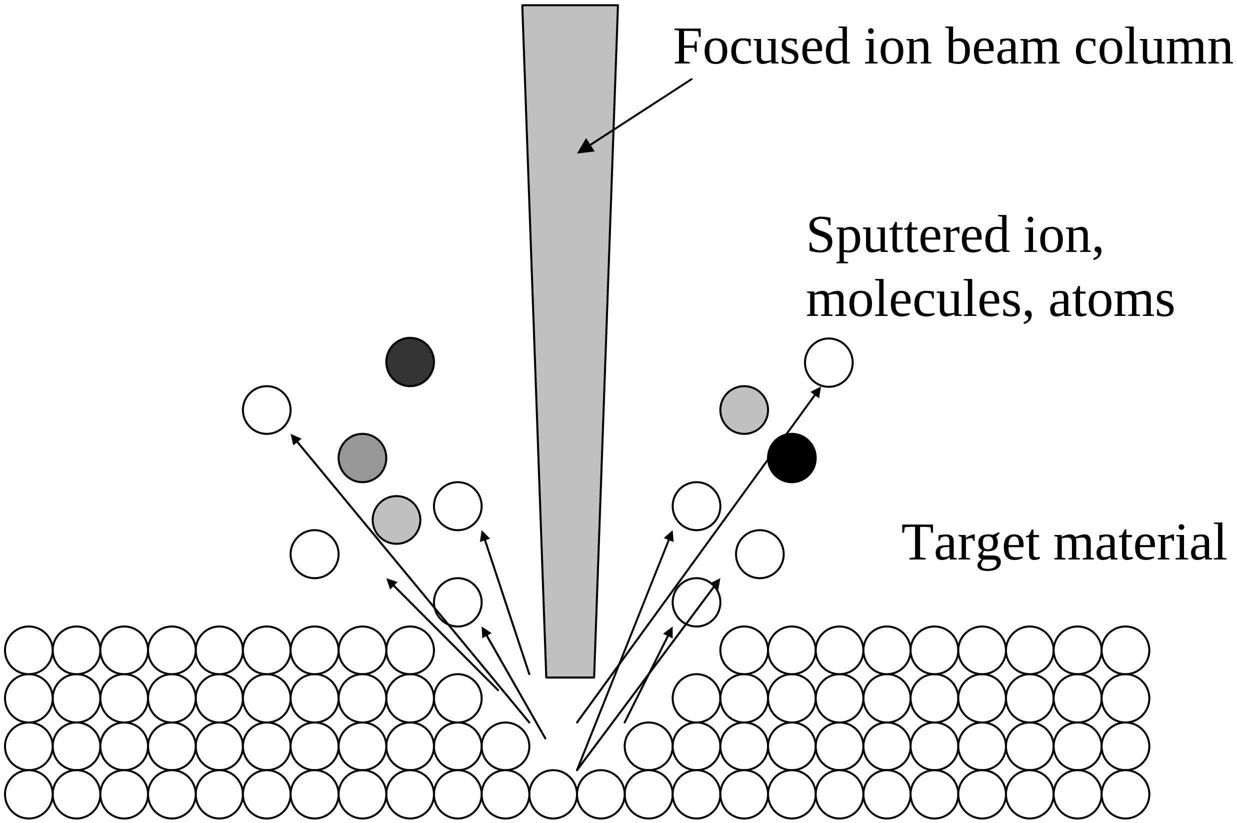
Frequency	Power [dB	with anten
10	30	0.0034
10.05	30	0.0042
10.1	30	0.0094
10.15	30	0.0268
10.2	30	0.0302
10.25	30	0.0134
10.3	30	0.0128
10.35	30	0.0104
10.4	30	0.0056
10.45	30	0
10.5	30	0.0018
10.55	30	0.0018
10.6	30	0.0016

Direct injection

Frequency	Power	Vout
10	-6	0.0048
10	-5.5	0.0052
10	-5	0.014
10	-4.5	0.0144
10	-4	0.0276
10	-3.5	0.016
10	-3	0.0208
10	-2.5	0.0436
10	-2	0.0524
10	-1.5	0.068
10	-1	0.0736
10	-0.5	0.0848
10	0	0.0992

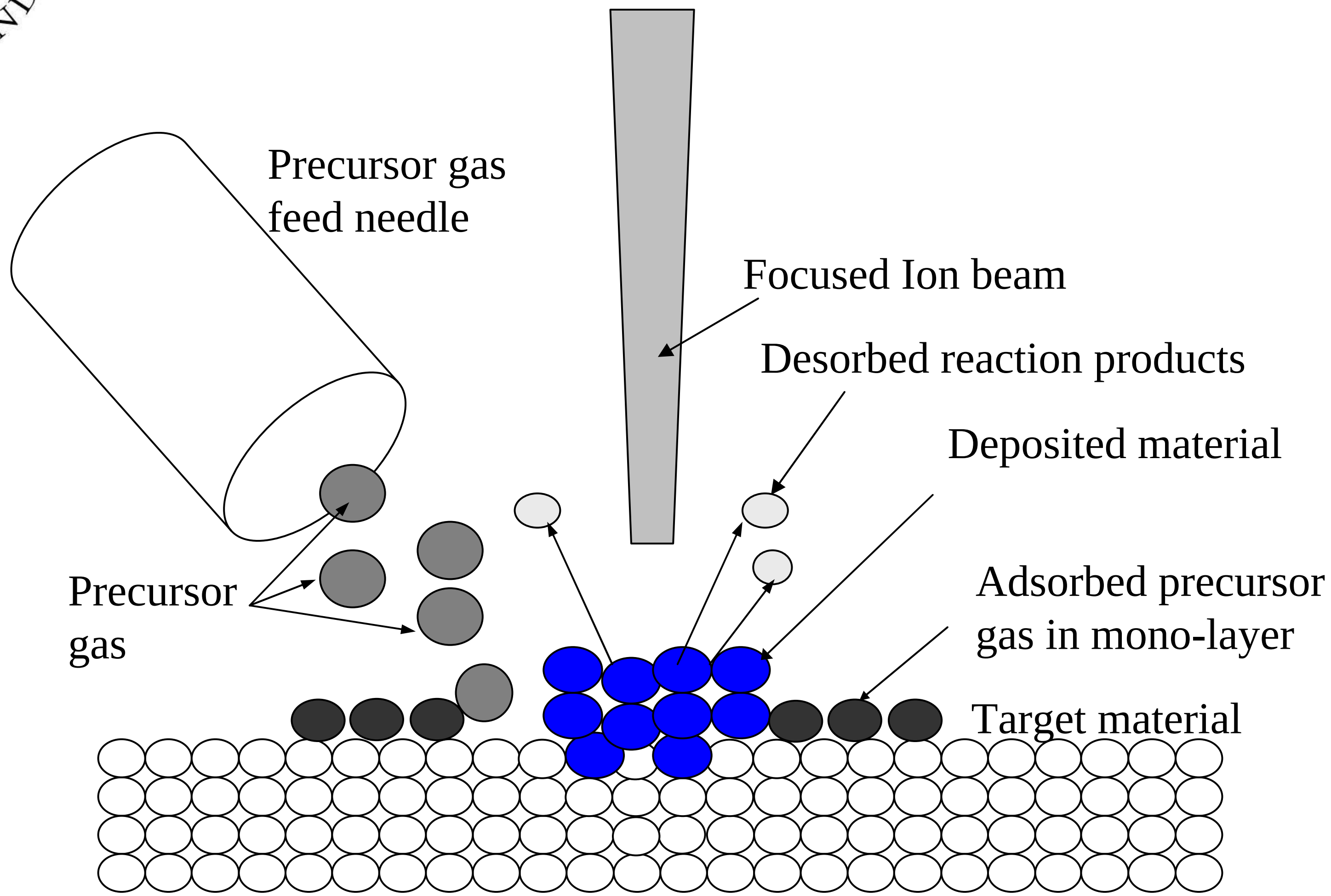
30dBm radiation made the same output voltage as -2.8dBm direct injection

FIB milling



Ion column focused on the location to be milled. Atoms, electrons, and molecules are sputtered from the target material

FIB ion induced deposition



Ion column focused on the location for deposition.
Similar to Chemical Vapor Deposition.