الراديو
كلية الهندسة - جامعة عين شمس
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Advances in Microwave & Millimeter-wave Integrated Circuits

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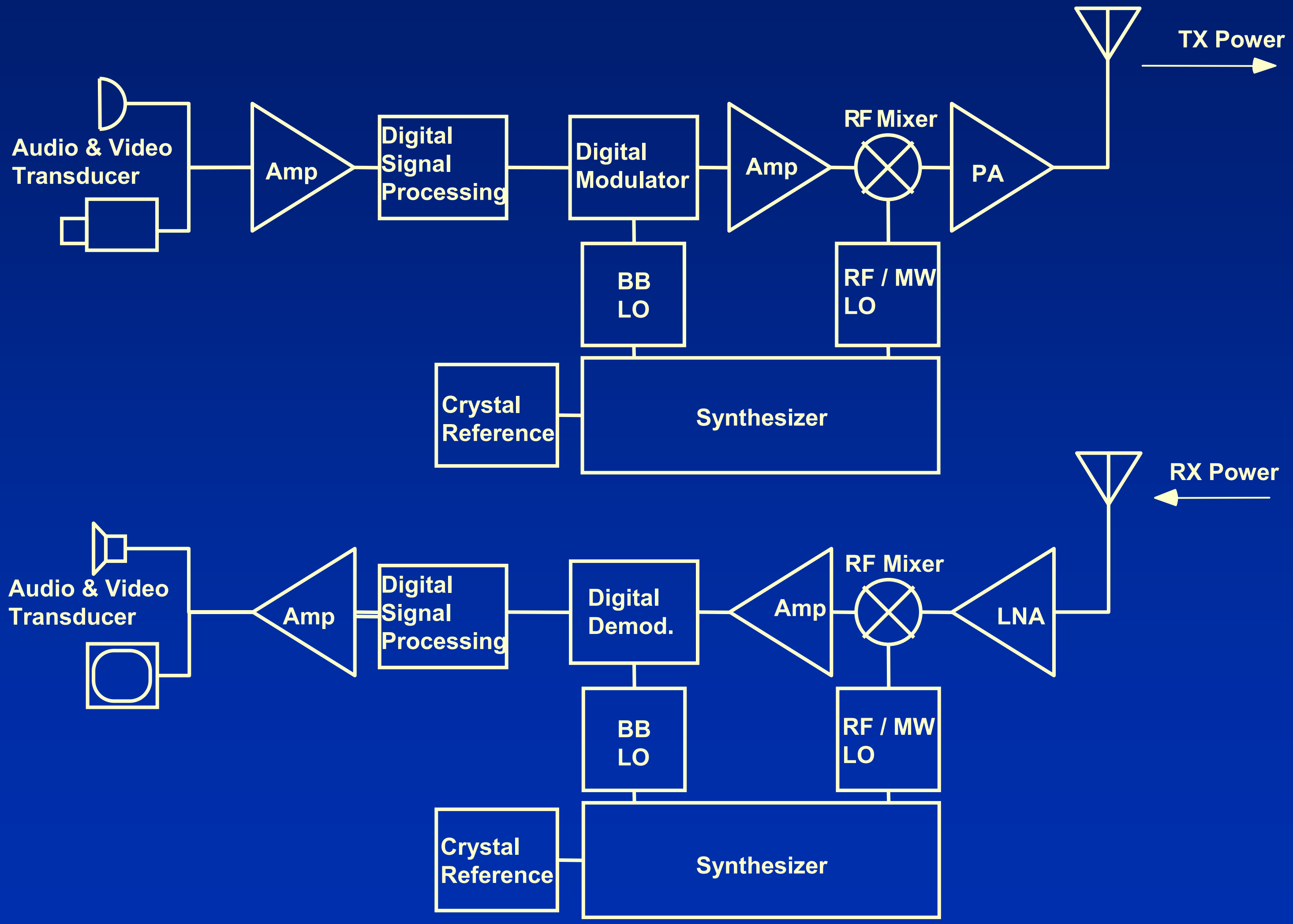
Presentation Outline

- Introduction to MMICs
- MMIC semiconductors and devices
- MMIC manufacturing and packaging
- MMIC design guidelines
- MMIC surveys and examples of novel MMIC circuits
- Conclusion and future trends

Wireless Systems Outline



MMIC Applications

- Linear Components:
  - Switches: SPDT, SPNT, NPMT, ..etc
  - Amplifiers: LNAs, PAs, Drivers
  - Attenuators: Fixed, variable, digital
  - Phase Shifters: Fixed, variable, digital
- Nonlinear Components:
  - Mixers
  - Frequency Multipliers
  - VCOs
  - Phase Detectors
  - Integrated Digital Circuits with RF circuits
- Subsystems
  - RF front end: Down/Up-converters, LNB
  - PLL
  - Transmit/Receive Modules

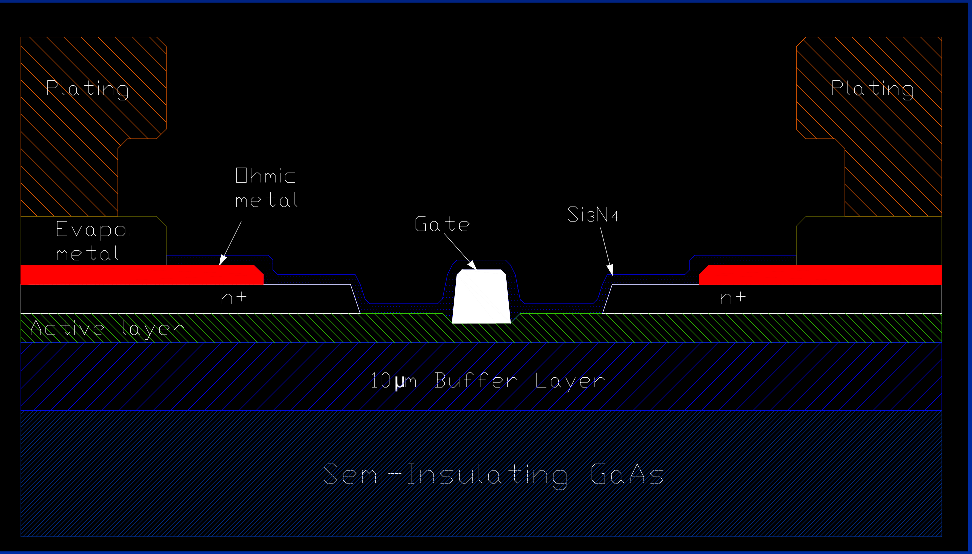
MIC versus MMIC Solution?

- MIC Advantages:
  - Fast & Low Cost Development
  - Better Performance such as: NF, Efficiency, P_{1dB}
  - Variety of Dielectric Materials
  - Integration of Different Semiconductor Technologies: Mesfets, Bipolar, Pin Diodes, Digital…etc
  - Higher Levels of Integration is possible
- MMIC Advantages:
  - Low unit Cost
  - Performance Uniformity from Unit to Unit
  - Very Small Size
  - Very Broadband Performance due to few parasitic effects
  - Simple Assembly Procedure

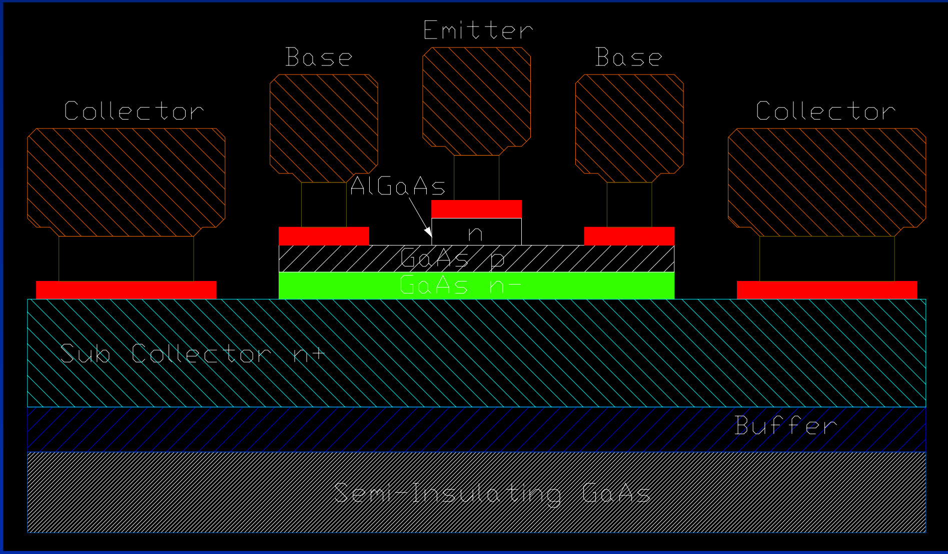
Semiconductor Materials for MMICs

MMIC Semiconductors	**Electron Mobility**	**ε_r**	**RF Loss**	**Thermal Conductivity**	**Active Device Technology**	**Application**
Gallium Arsenide (GaAs)	0.85m^2/V/s	12.9	Low	46 W/ºC/m	MESFET, HEMT, pHEMT, HBT, mHEMT	PA, LNA, mixers, attenuators, switches, …etc
Silicon (Si)	0.14m^2/V/s	11.7	High	145 W/ºC/m	LDMOS, RF CMOS, SiGe HBT (BiCMOS)	Mature for low power mixed signal applications
Silicon Carbide (SiC)	0.05m^2/V/s	10	Low	430 W/ºC/m	MESFET	Very high power below 5GHz
Indium Phosphide (InP)	0.60m^2/V/s	14	Low	68 W/ºC/m	MESFET, HEMT	mm-wave
Gallium Nitride (GaN)	0.08m^2/V/s	8.9	Low	130 W/ºC/m	HEMT	High power, limited availability

FET & Bipolar Device Structures



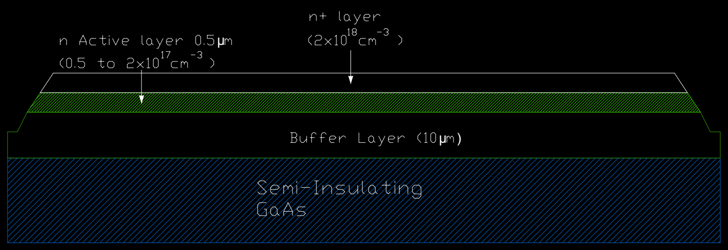
Typical FET Structure



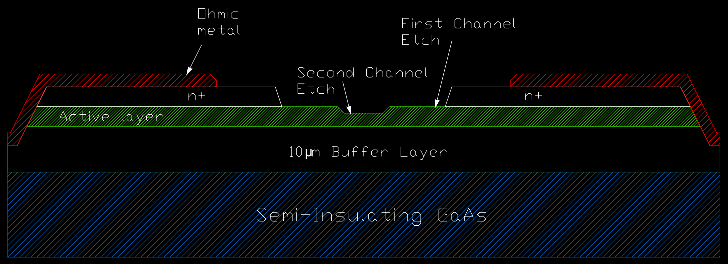
Typical HBT Structure

(Not to scale)

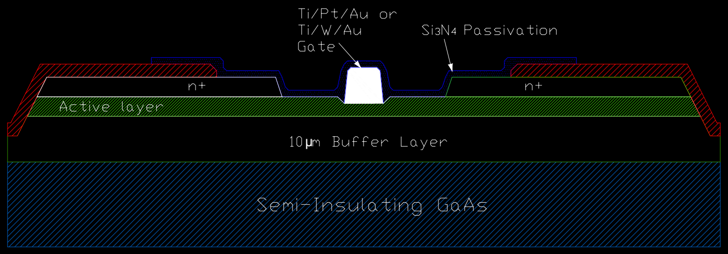
Typical Fabrication Steps of GaAs MESFET Process



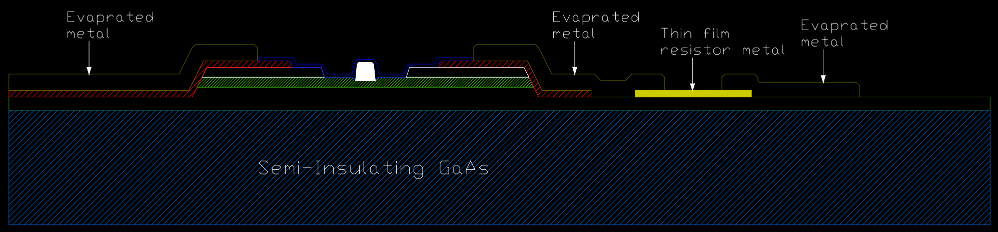
a) Active Layer Mesa



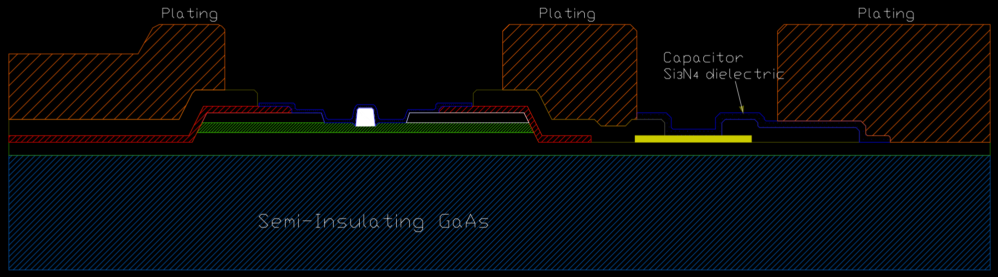
b) Gate first & second etch
& Ohmic metal



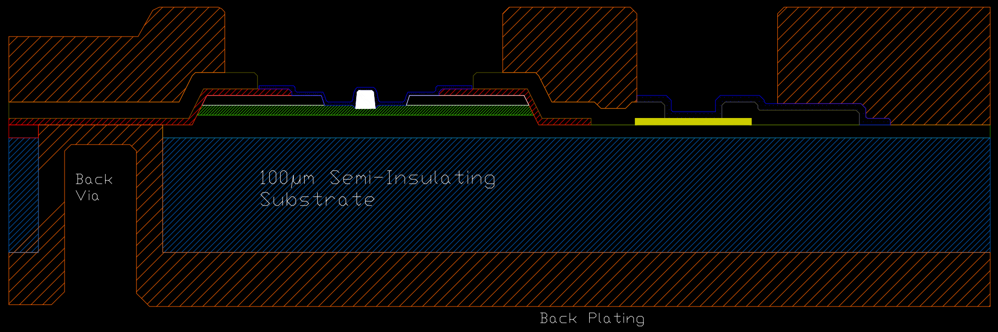
c) Gate metal & passivation



d) Thin film resistor & capacitor bottom metal



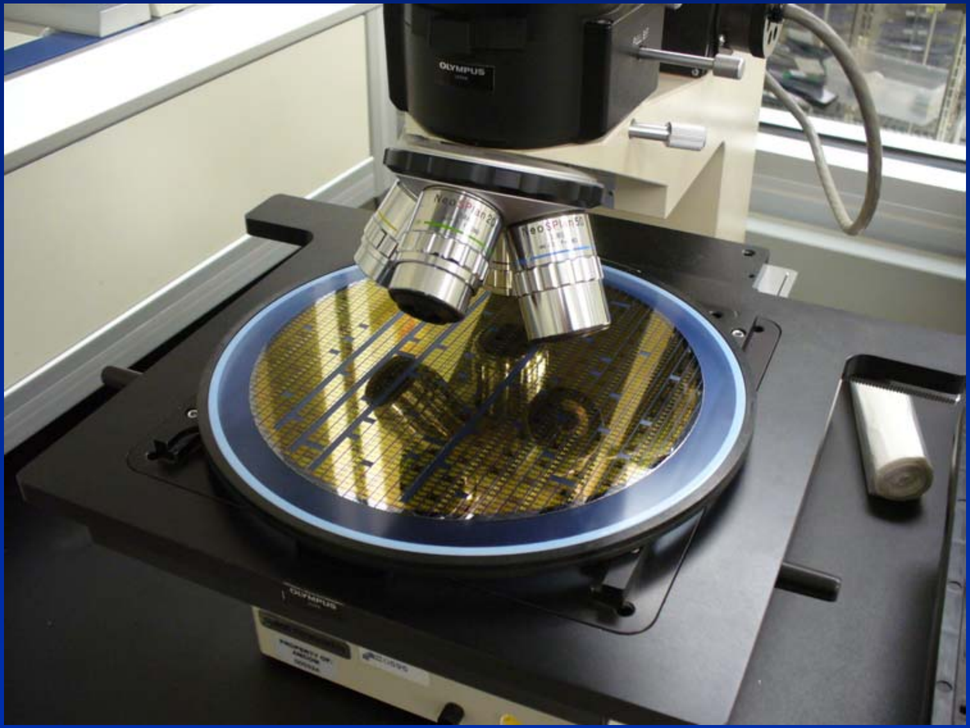
e) Capacitor dielectric & top plating

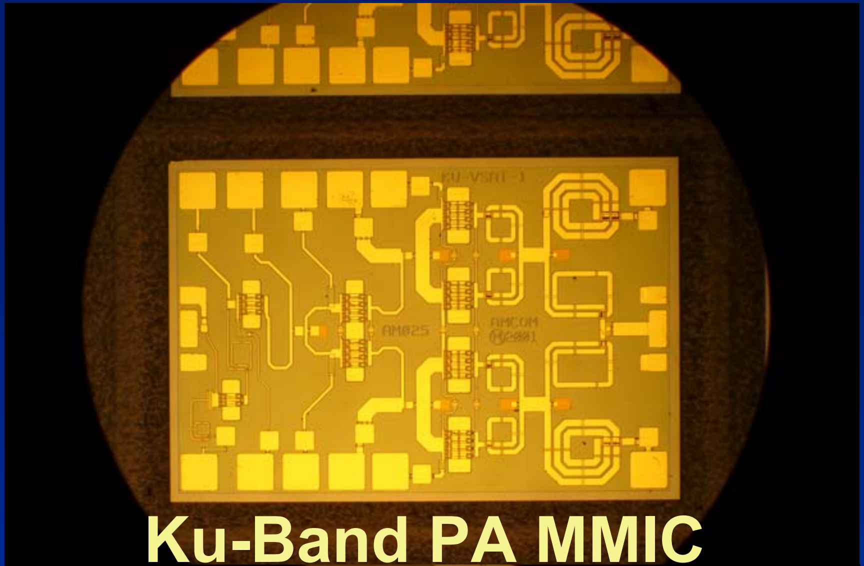


f) Wafer lapping, back via & back plating

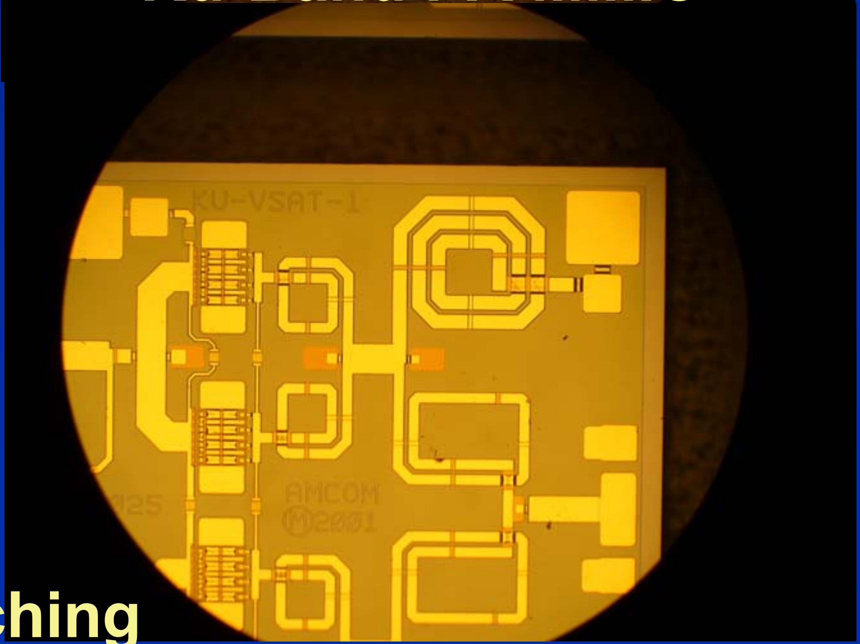
Wafer & MMIC Examples

6” GaAs wafer



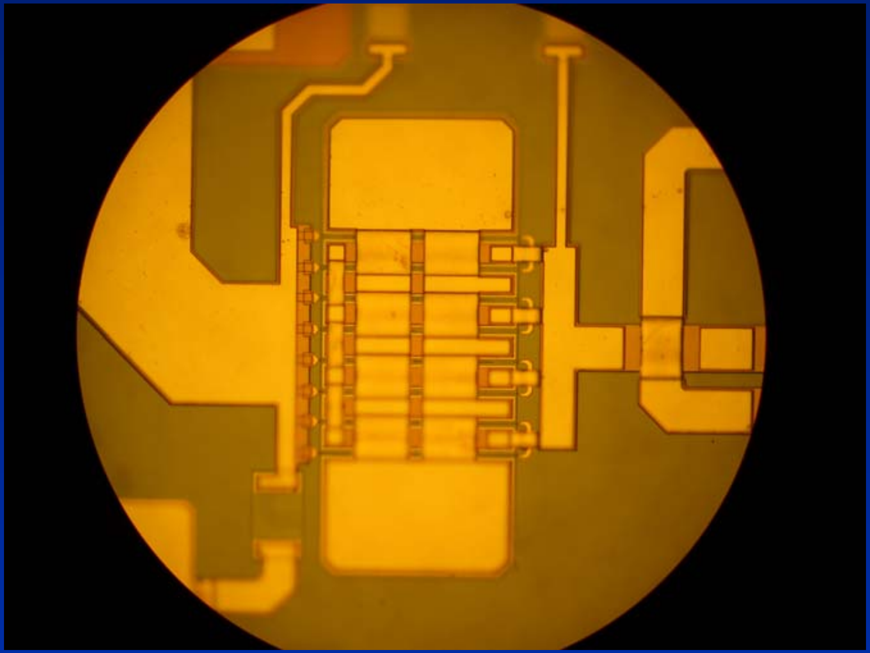


Ku-Band PA MMIC

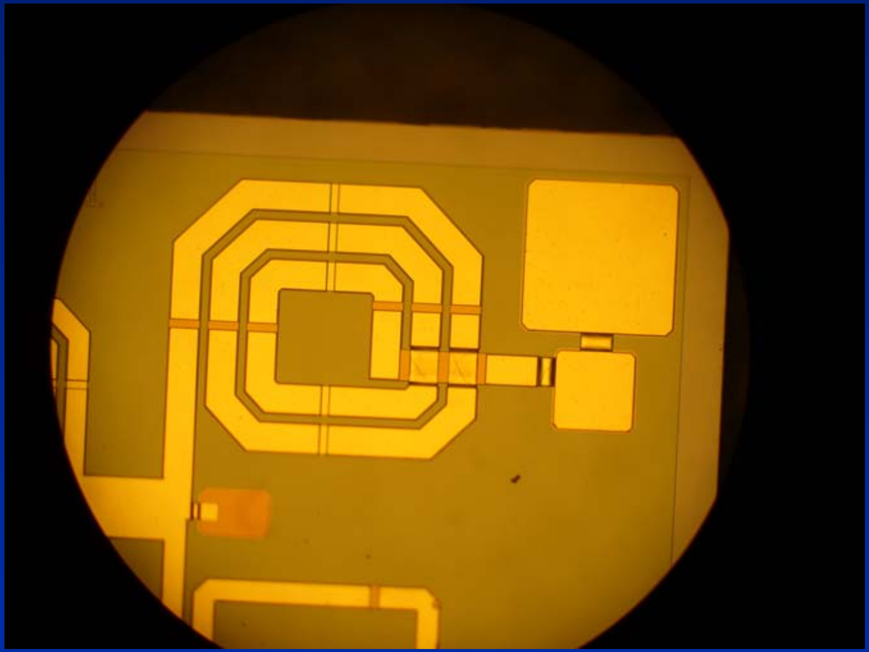


Output Matching

MMIC Component Snapshots



Single FET



MMIC Components

MMIC Recommended Processes

Application	Frequency	Device Process
Low Noise Amplifiers	1-10GHz	GaAs Mesfet
	10 –100Ghz	GaAs pHEMT
	> 100GHz	InP
Medium Power (< 10W)	1 -10GHz	GaAs HBT, GaAs Mesfet
	10 – 100GHz	pHEMT
High Power (> 100W)	1 - 10GHz	GaAs Mesfet, GaN, SiC
	10 – 30GHz	GaN
Switches for digital attenuators and phase shifters	0.1 – 20GHz	Mesfet
	20–100GHz	pHEMT
Low Power Mixed Signal	1 – 50GHz	SiGe BiCMOS
VCO	1 -100GHz	GaAs HBT

List of MMIC Foundries Worldwide

Foundry	Location	Capability	Processes offered	Market
Cree	Durham, NC, USA	3" SiC & GaN	GaN HEMT & SiC Mesfet	Offers SiC foundry services & has a product line
Filtronics Compound Semiconductors	Santa Clara, CA, USA	6” GaAs	0.2µm pHEMT	Offers foundry services & has a product line
GCS	Torrance, CA, USA	6” GaAs	0.5µm pHEMT, InGaP & InP HBT	Only offers foundry services
IBM	Burlington, VT, USA	Silicon	0.18µm,0.25µm,0.35µm,0.5µm SiGe BiCMOS & 0.13µm, 0.18µm,0.25µm RFCMOS	Only offers foundry services
Knowledge ON	Iksan, S. Korea	6” GaAs	InGaP HBT	Offers foundry services & has a product line
M/A COM	Lowell, MA & Roanoke, VA, USA	4” GaAs	0.18µm ,0.5µm & 1µm pHEMT,0.5µm & 1µm Mesfet, MSAG	Offers foundry services & has a product line
Nitronex	Raleigh, NC, USA	GaN on 4“ Silicon	GaN HEMT	Offers new foundry services & has a product line
SiGe Semiconductor	Ottawa, Ontario, Canada	SiGe	SiGe BiCMOS	Offers foundry services & has a product line
Transcom	Tainan, Taiwan	6” GaAs	0.25µm & 0.5µm PHEMT, HFET & MESFET	Offers foundry services & has a product line
Triquint Semiconductor	Portland, OR & Dallas, TX, USA	6” GaAs & GaN	0.15µm MHEMT,0.13,0.25, 0.35, 0.5µm pHEMT,0.5µm & 0.6µm Mesfet, 0.5µm, HFET,3µm InGaP HBT	Offers foundry services & has a product line
United Monolithic Semiconductor	Ulm, Germany Orsay, France	4” GaAs	0.15µm, 0.25µm pHEMT and 2µm HBT	Offers foundry services & has a product line
WIN Semiconductor	Tao Yuan Shien, Taiwan	6” GaAs	0.15µm, 0.5µm pHEMT and 1µm , 2µm HBT	Only offers foundry services

Essential MMIC Assembly Equipment

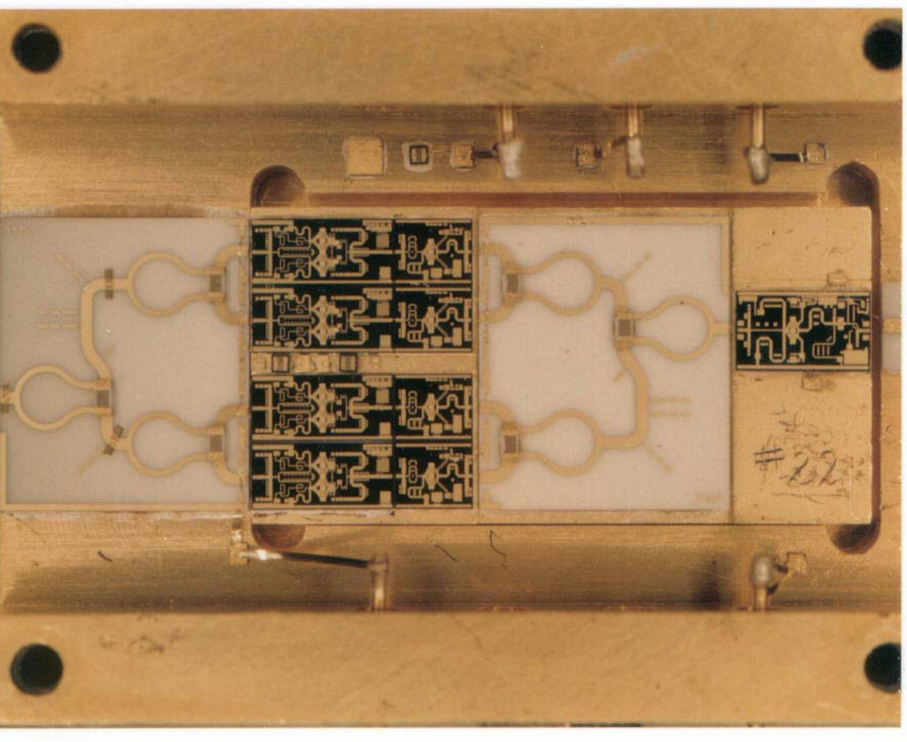

Class 10,000 Clean Room


Eutectic Die Attach

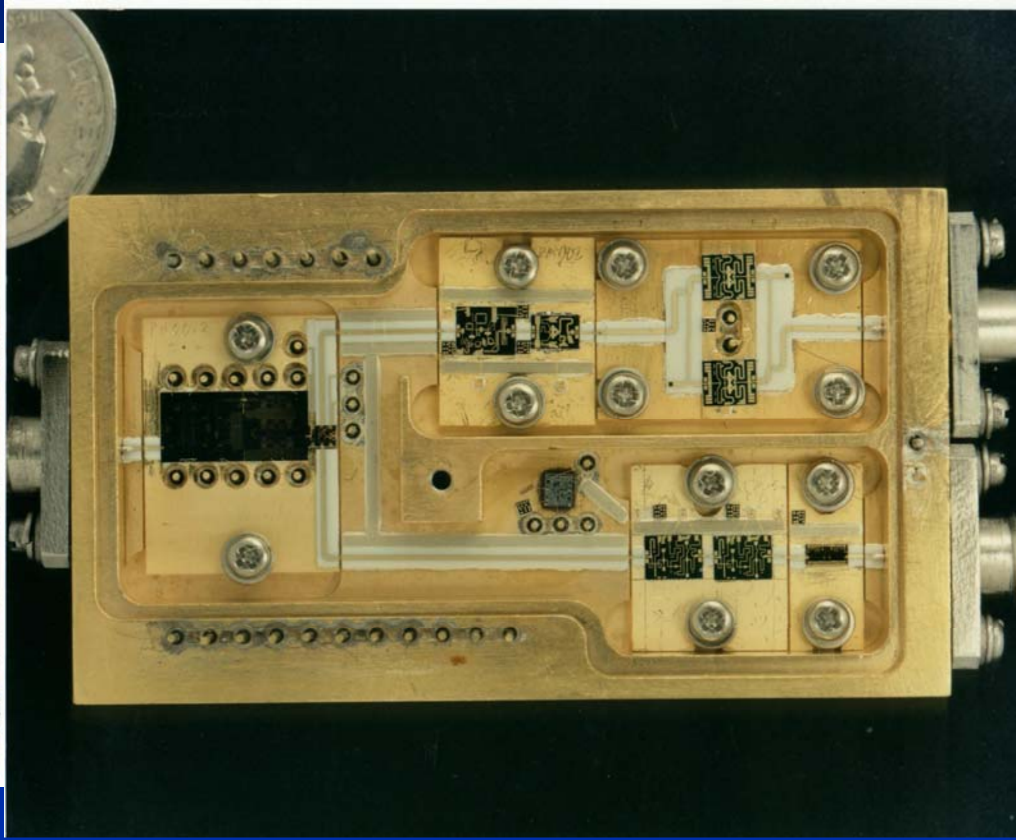

Die Pick & Place


Automatic Bonder

Packaging Examples: Carrier mounted

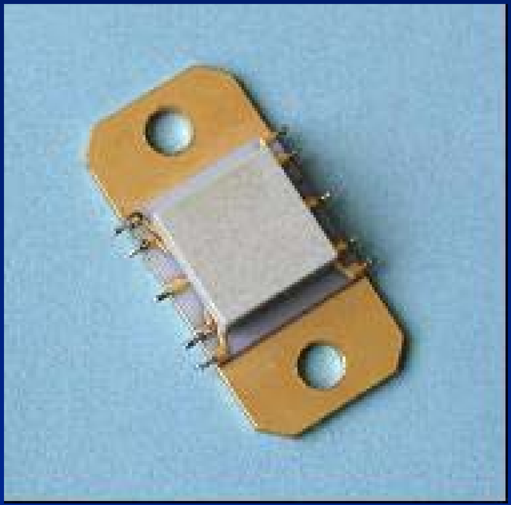


10W Module

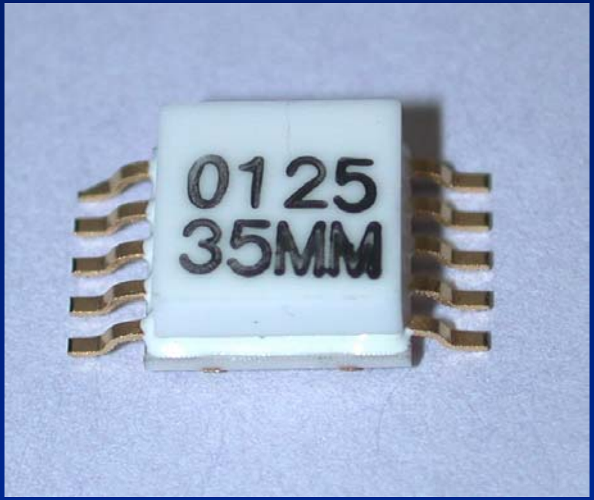


C-Band T/R Module

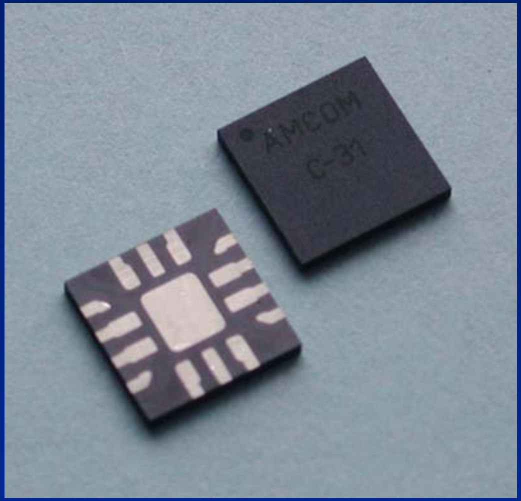
Low Cost Packaged MMICs & Devices



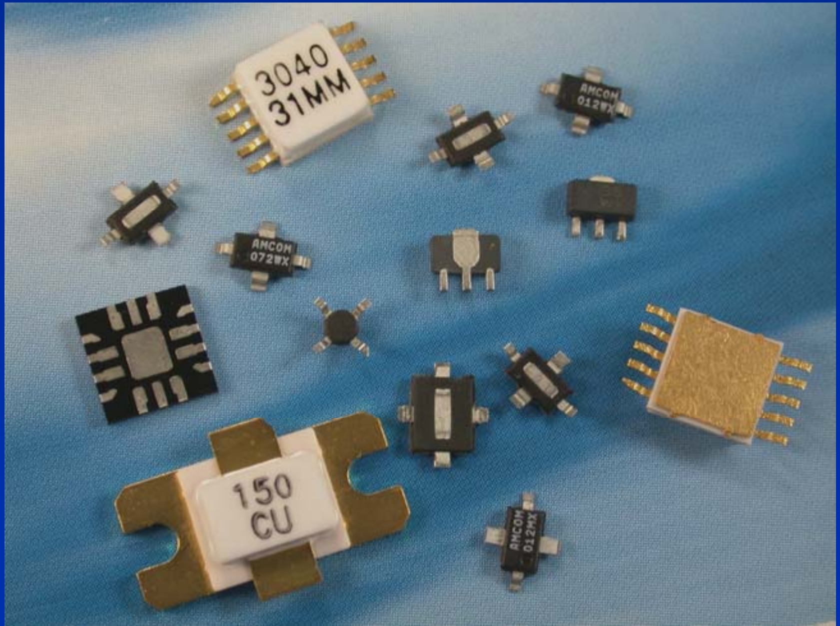
a) Ceramic Drop-in



b) SMT Ceramic

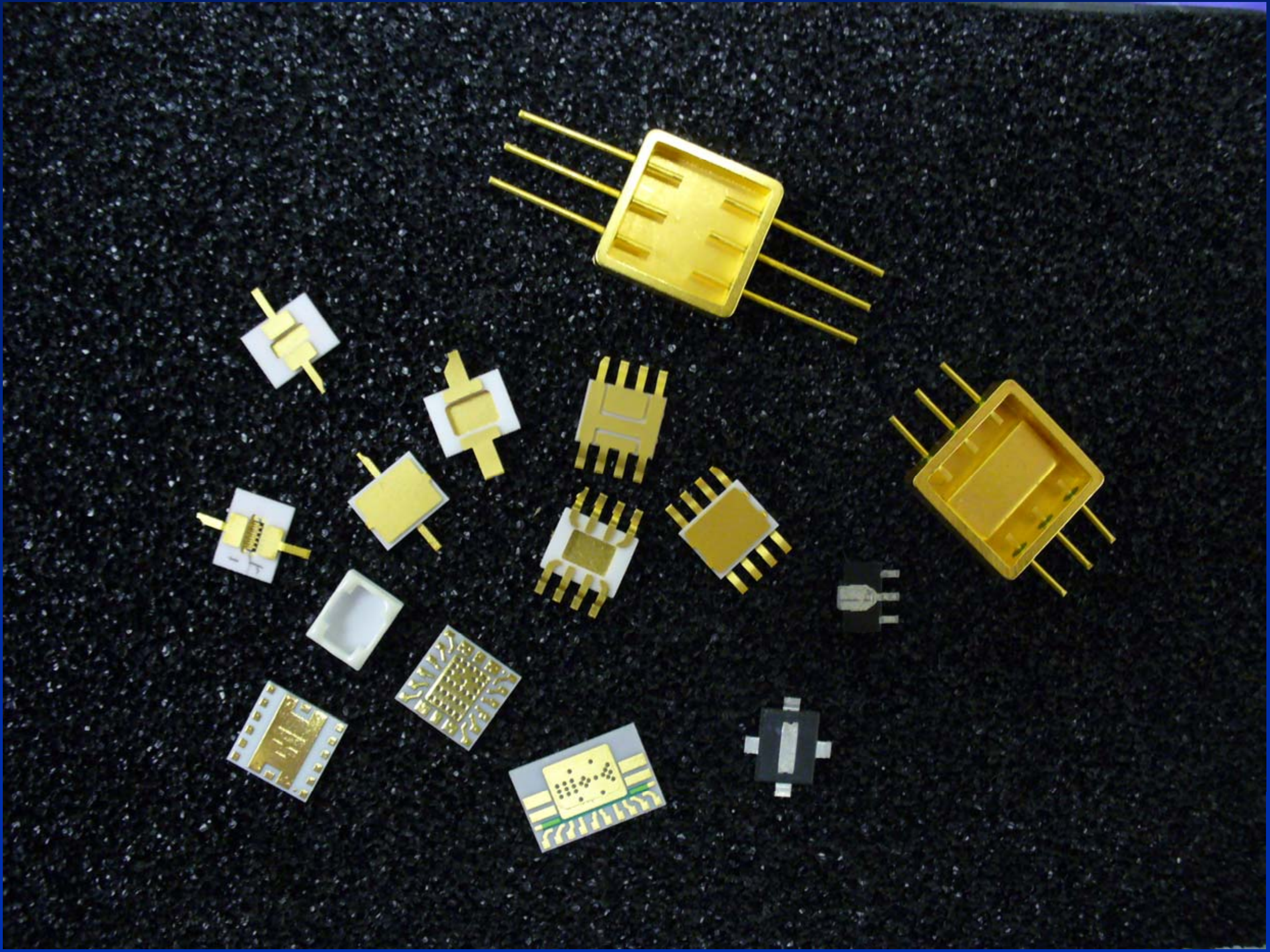


c) SMT Plastic

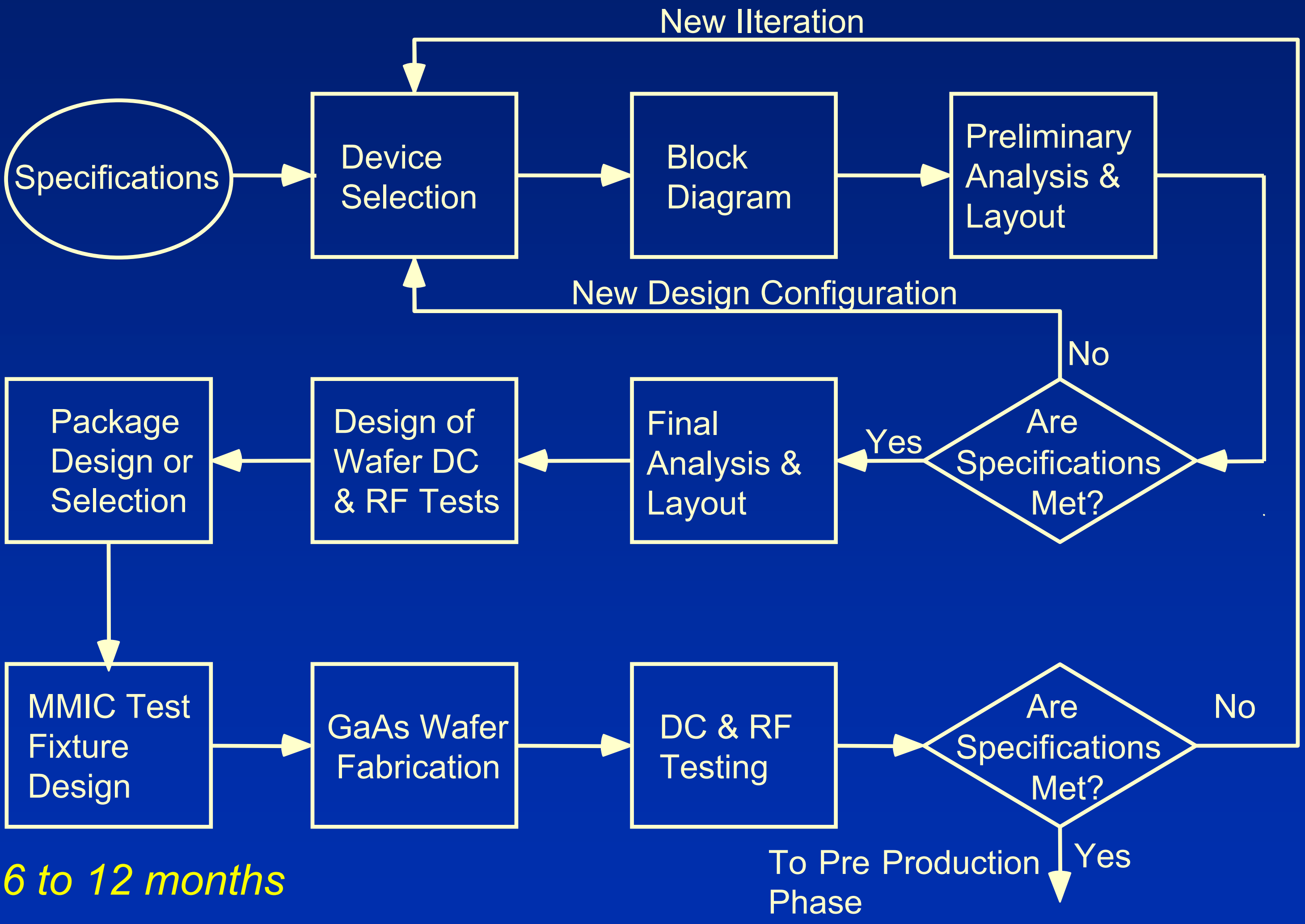


d) Finished Products

MMIC & Device Empty Packages



MMIC Development Steps



New IIteration

Specifications

Device Selection

Block Diagram

Preliminary Analysis & Layout

New Design Configuration

No

Are Specifications Met?

Yes

Final Analysis & Layout

Design of Wafer DC & RF Tests

Package Design or Selection

MMIC Test Fixture Design

GaAs Wafer Fabrication

DC & RF Testing

Are Specifications Met?

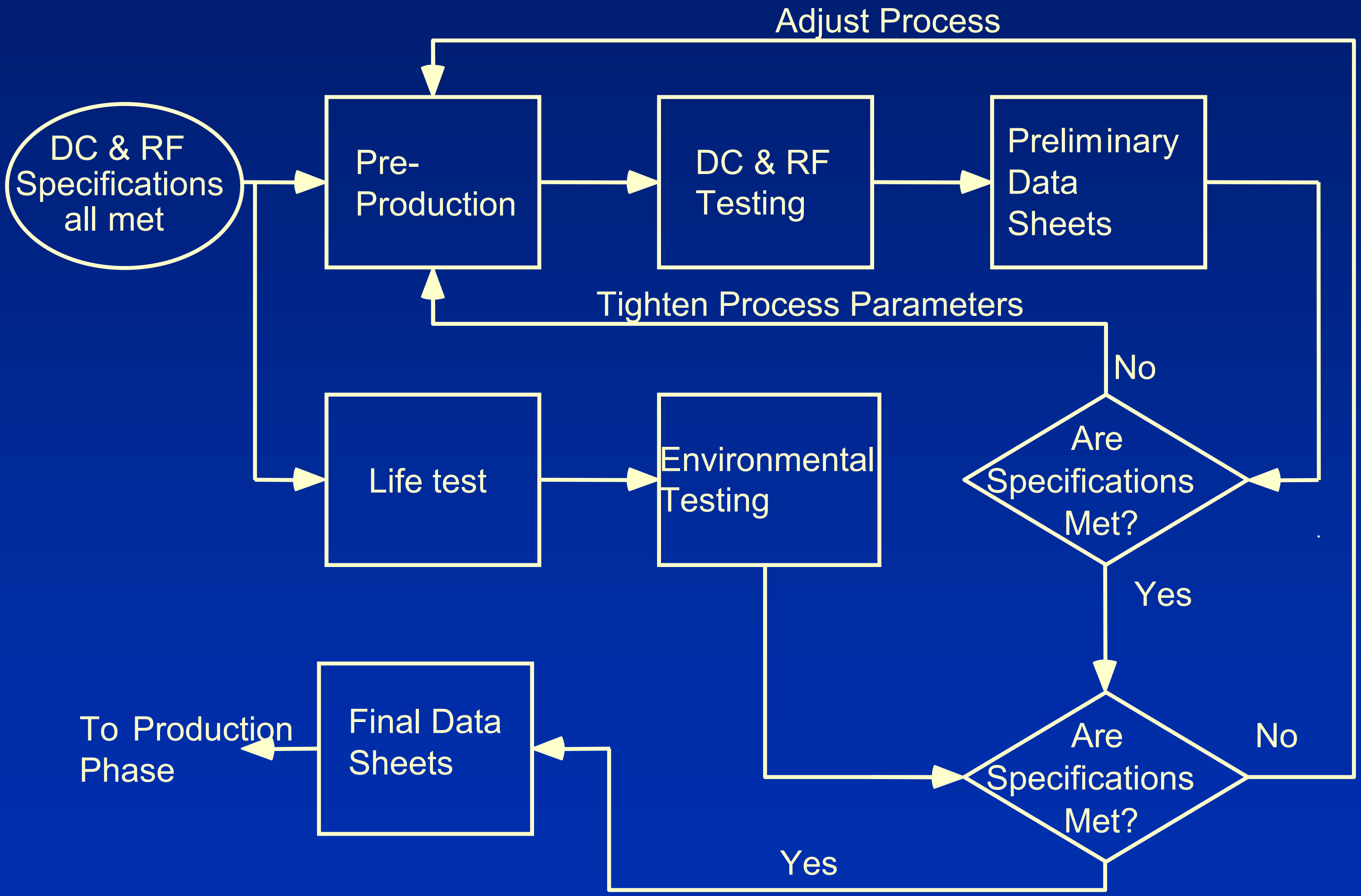
No

Yes

To Pre Production Phase

- *6 to 12 months*
- *Foundry Service: $50,000 - $120,000*

MMIC Production Steps



Adjust Process

DC & RF Specifications all met

Pre-Production

DC & RF Testing

Preliminary Data Sheets

Tighten Process Parameters

No

Life test

Environmental Testing

Are Specifications Met?

Yes

To Production Phase

Final Data Sheets

Are Specifications Met?

No

Yes

MMIC DESIGN GUIDELINES

- Device Characterization
- Device Scaling
- Circuit Design and Simulation
- Chip Yield
- Thermal Analysis
- MMIC testing

Device Characterization

- Device characterization accounts to 50% of design effort.
- Small signal testing include: S-parameters, NF …etc
- Large signal testing: DC data, I-V characteristics, power load-pull, efficiency, IMD & EVM
- Modeling should include all pads and transmission lines connected to test device

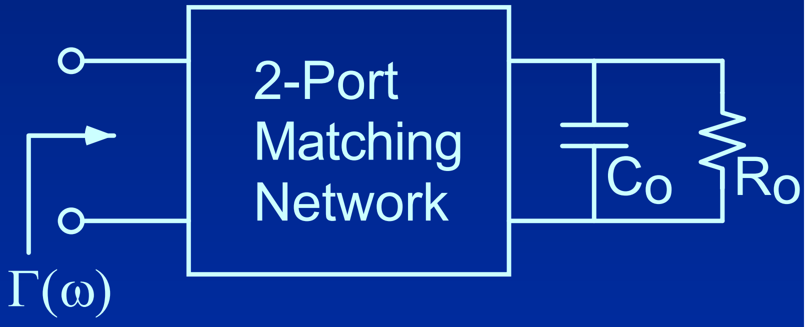
Device Scaling

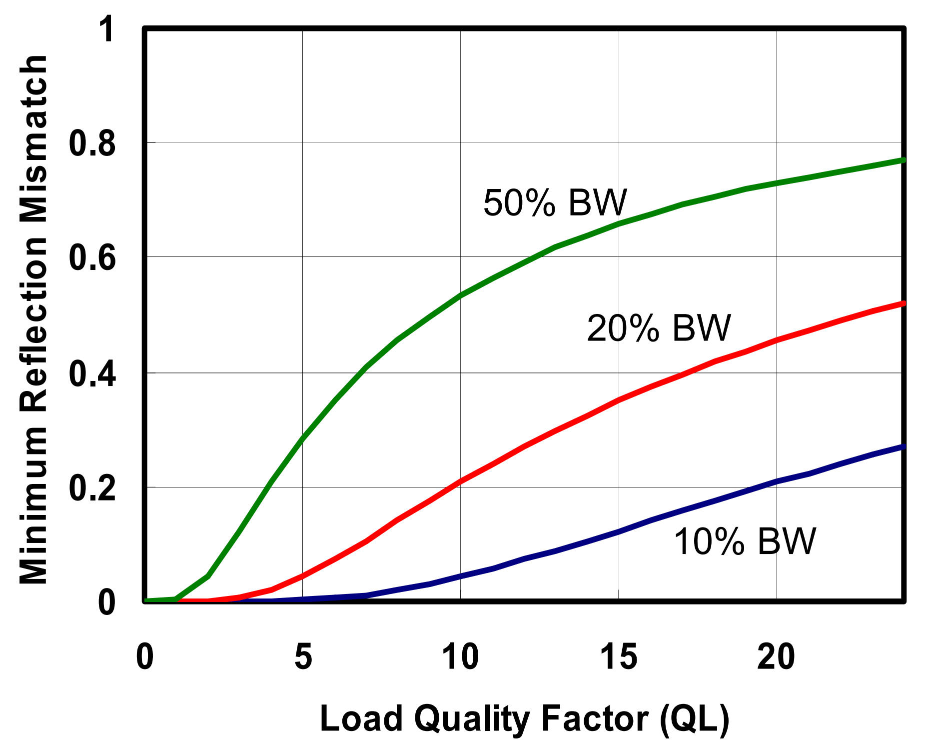
- Invariant parameters are: voltage, gain, NF, efficiency (η), linearity, f_{max} & f_T
- Scaled parameters such as: current, P_{1dB} , P_{sat} , Z_{in}, Z_{out}, Z_{opt} are all proportional to device periphery
- Device dimensions should be less than 5% of wavelength (λ)
- Device building block such as gate length (L_g) and gate width (W_g) cannot be scaled and should remain invariant.

MMIC Design & Simulation

- Make it simple and use small number of matching elements
- Bode / Fano Theorem implies using resistive matching to achieve broadband matching
- Keep at least one substrate height between elements to avoid EM coupling
- Understand sources of simulation errors: EM coupling, non-standard library elements, layout inaccuracy, process variations, modeling errors

Bode / Fano Theorem





$$\int_0^\infty \ln \frac{1}{|\Gamma(\omega)|} . d\omega \le \frac{\pi}{R_o C_o} \qquad |\Gamma|_{\min.} = \exp\left(-\frac{\pi}{(\omega_b - \omega_a) R_o C_o}\right)$$

Chip Yield

$$Yield = \exp(-A_g D_g - A_c D_c)$$

$$Chip\ Cost = \frac{Wafer\ Cost}{Wafer\ Area} A_m \exp(A_g D_g + A_c D_c)$$

A_g is the total MMIC device gate or emitter area

A_c is the total MMIC capacitor area

A_m is the MMIC chip area

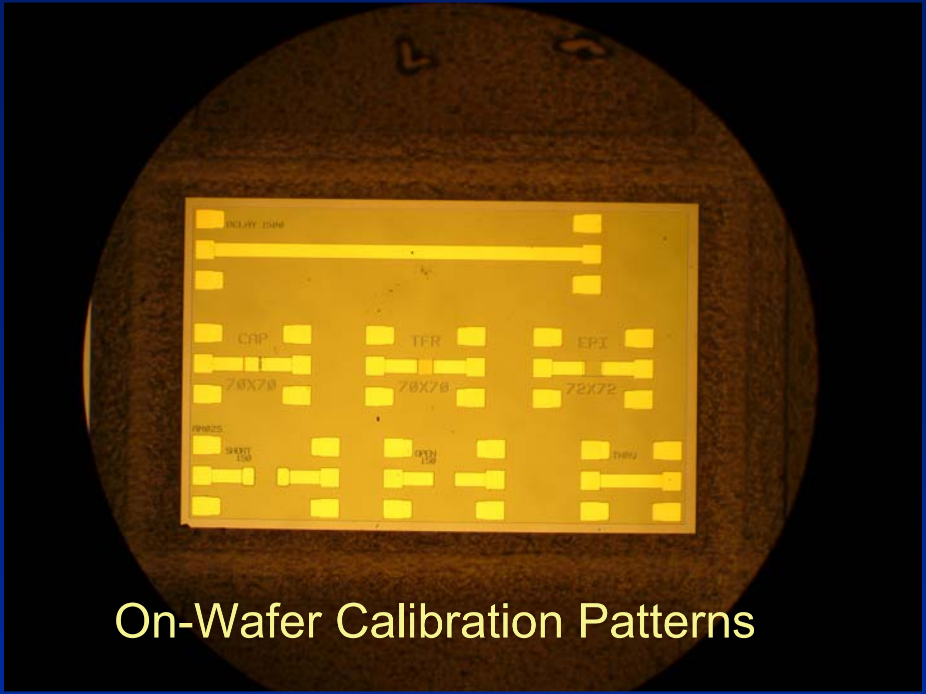
D_g & D_c are critical defects per unit area

- Maximum MMIC area is 10 to 20mm^2
- For very low cost the maximum area is usually < 2 to 3mm^2

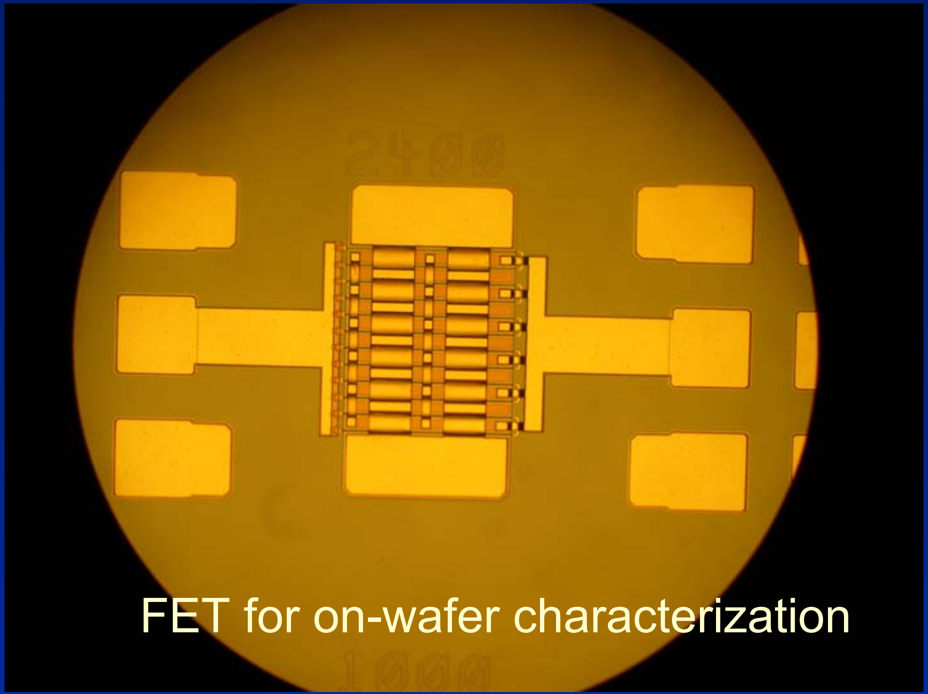
Thermal Analysis

- Maximum junction device temperature T_j < 175ºC
- High reliability applications < 120ºC
- Divide power stage device into small cells to spread the heat
- Take into account solder and package heat resistance when calculating T_j

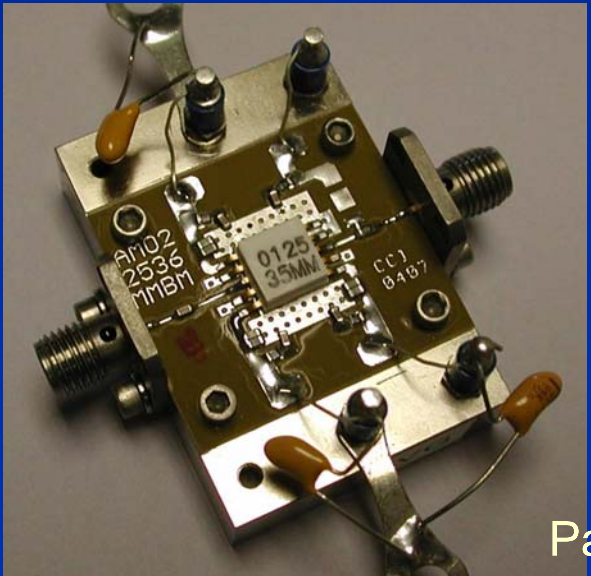
MMIC RF Testing



On-Wafer Calibration Patterns



FET for on-wafer characterization



Packaged MMIC TF

- S-parameters, power, IMD …etc
- On-wafer vs Test Fixture testing
- Calibration methods

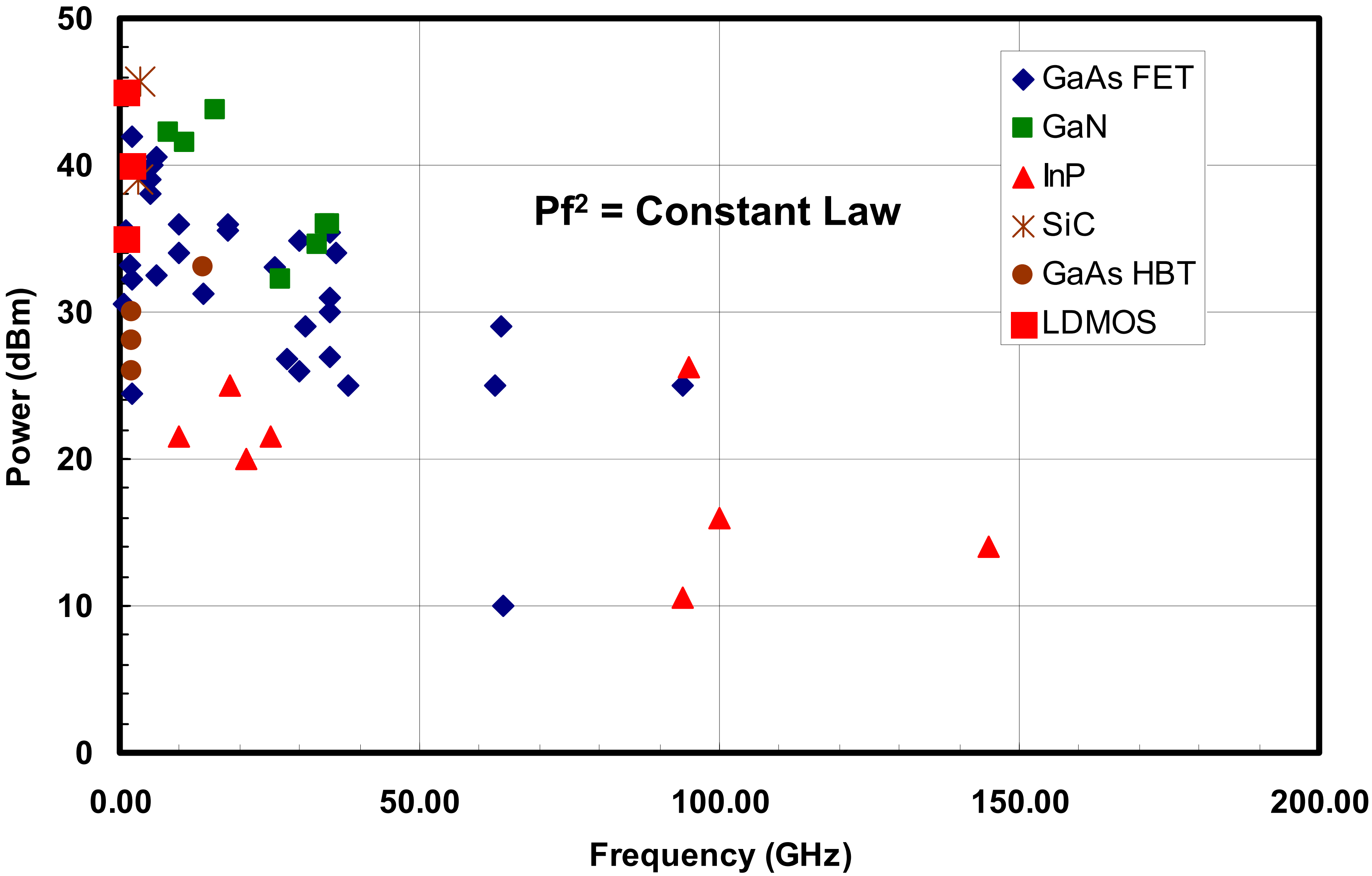
RF Measurement Equipment

Vector Network Analyzer

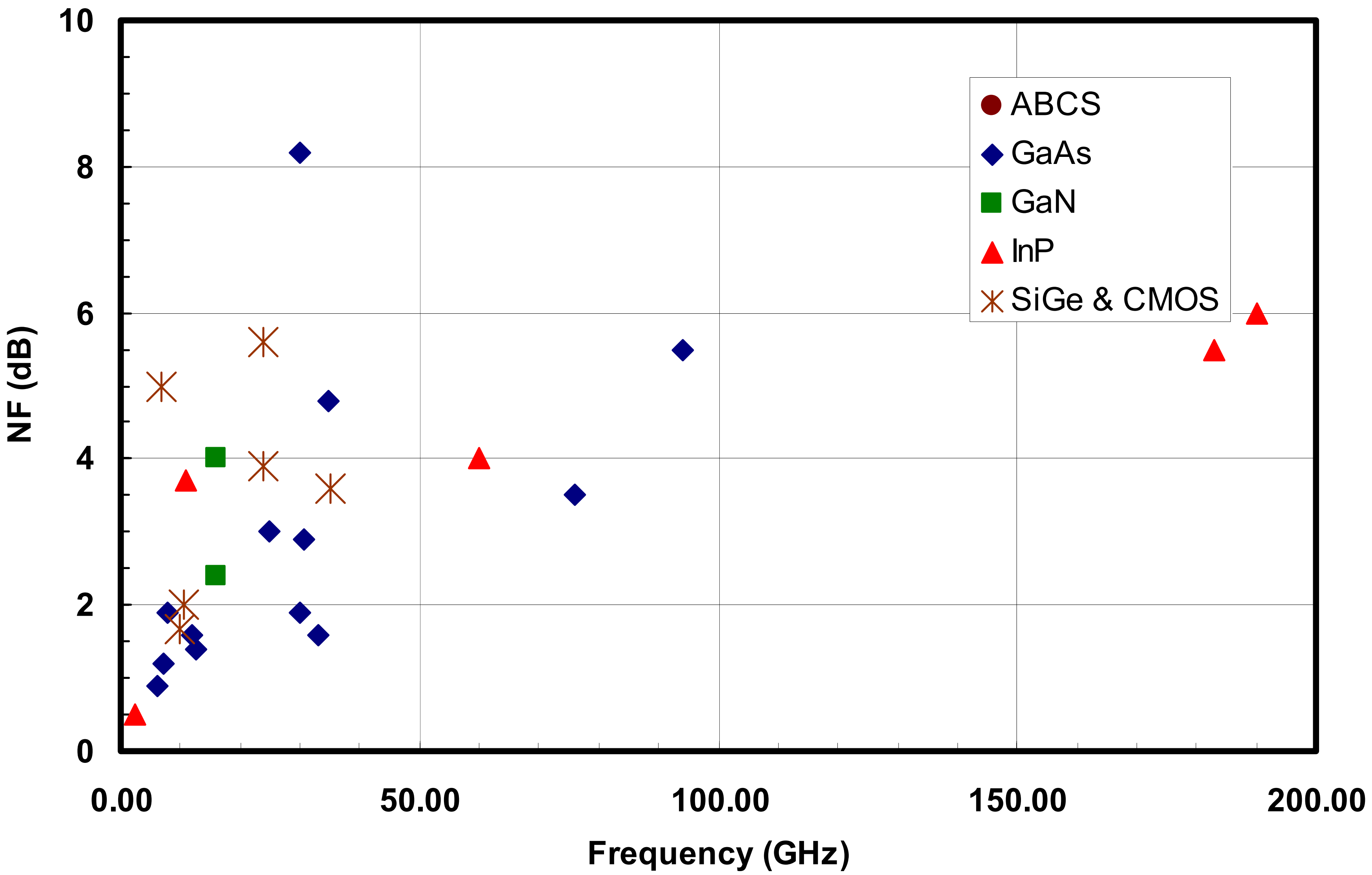
On-Wafer Probe Station

Automated Power Test Bench

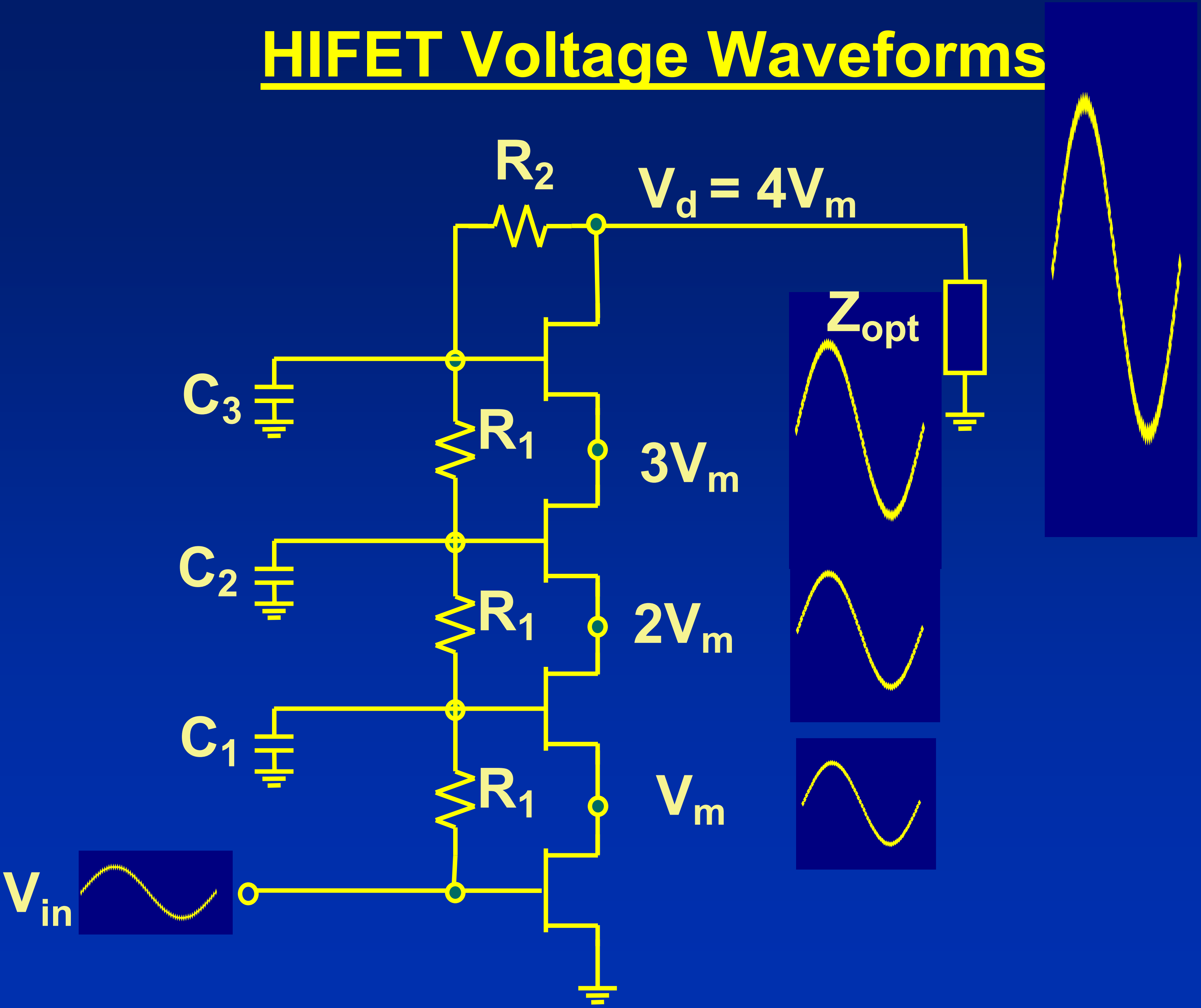
Power MMIC Survey



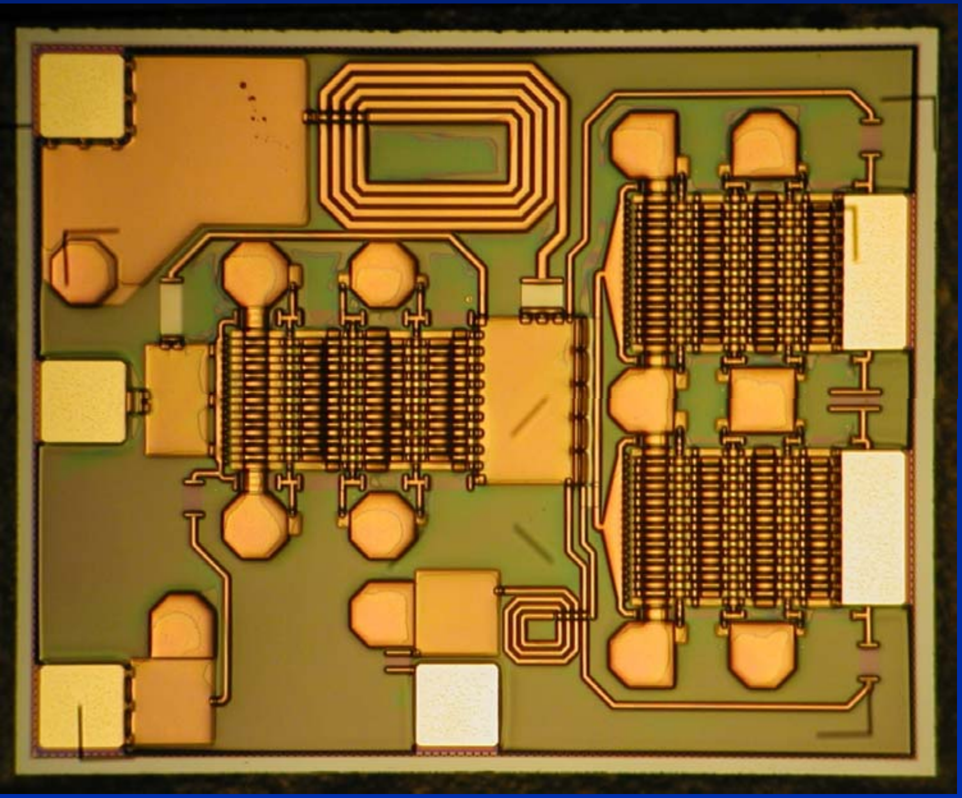
LNA MMIC Survey



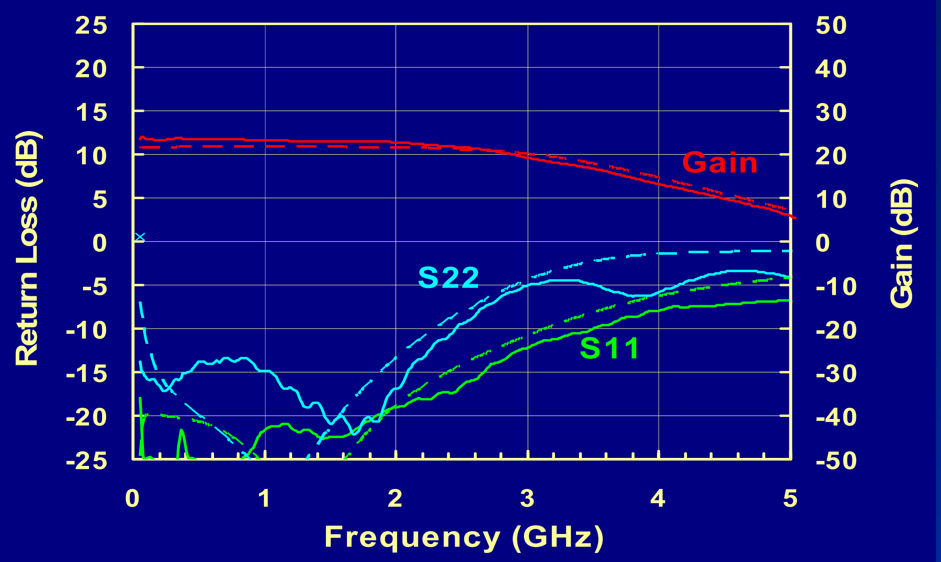
HIFET Voltage Waveforms



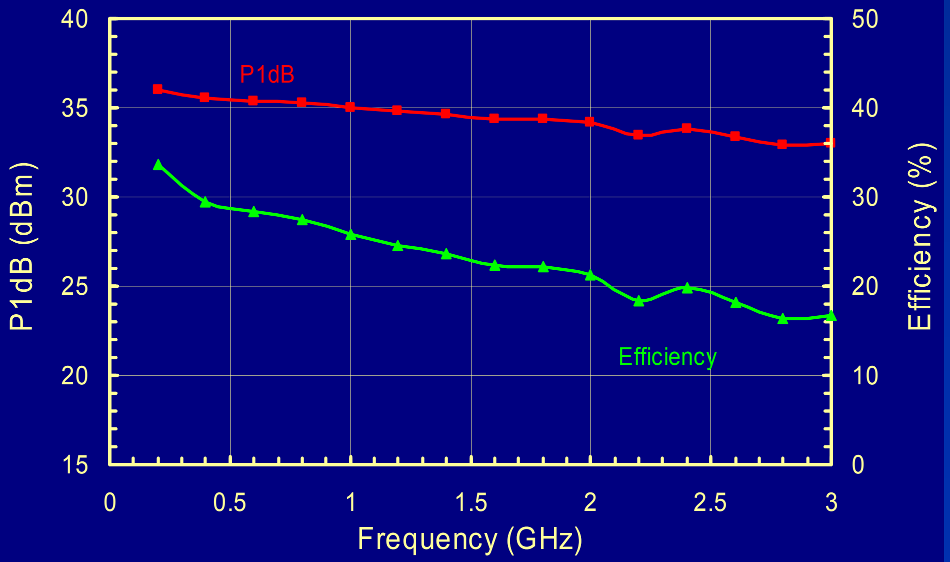
4W 0.03 to 3GHz HiFET MMIC



MMIC Photo
Die Size 2.2x1.8mm

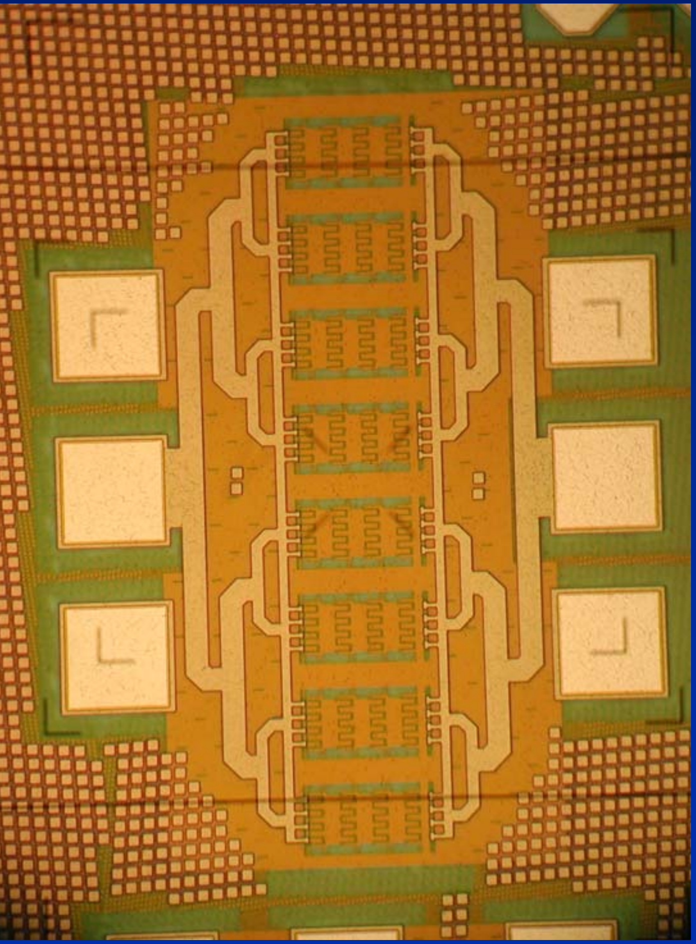


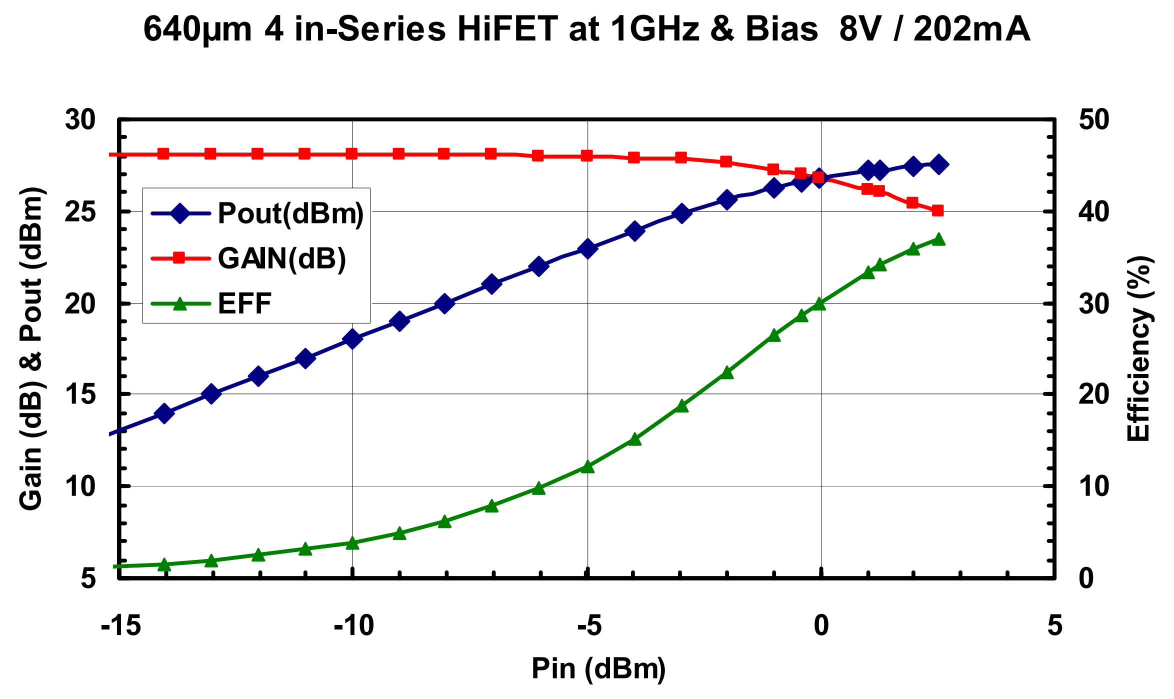
Bias 20V, 150mA, 400mA



Bias @ 20V/550mA

Power CMOS HiFET at 1GHz

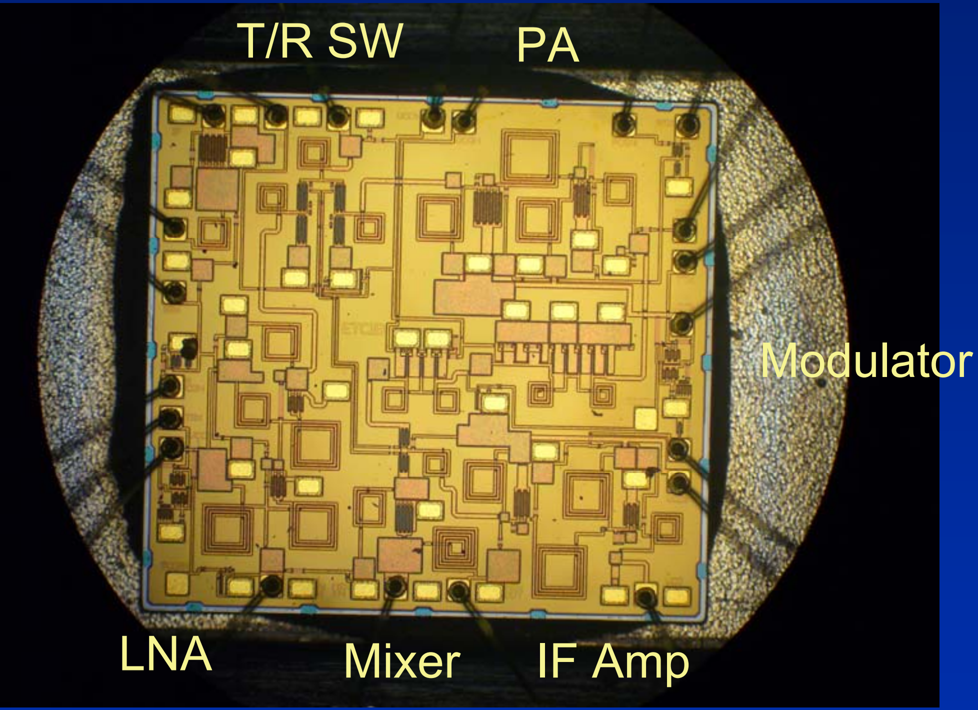




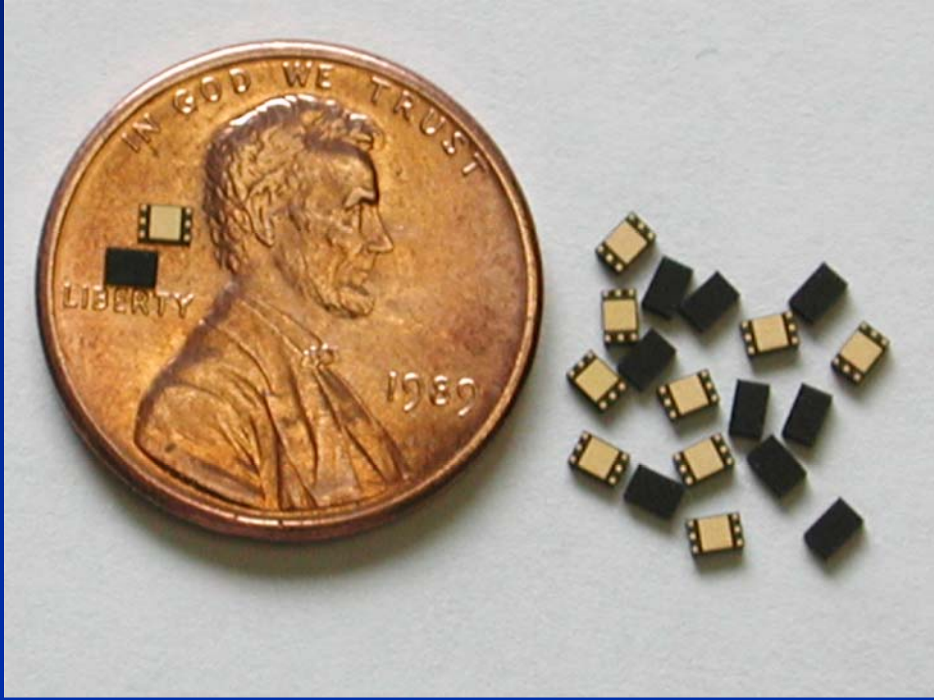
R_{opt}= 40 Ω

(2.5 Ω for 2560μm device)

MMICs for Wireless Applications

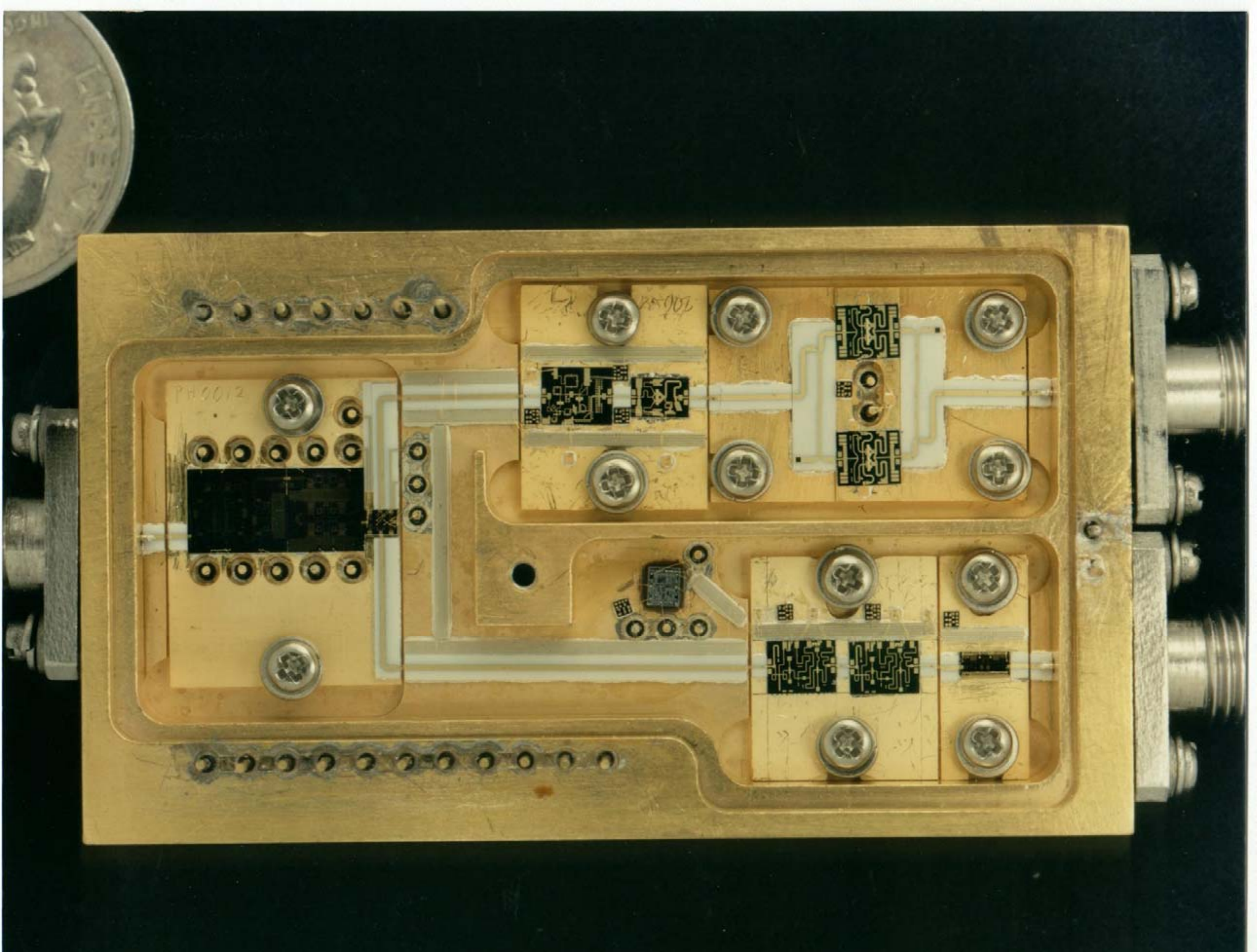


RF Front End for ETC Applications



MMIC PA for 802.11b

C-Band T/R Module for Phase Array

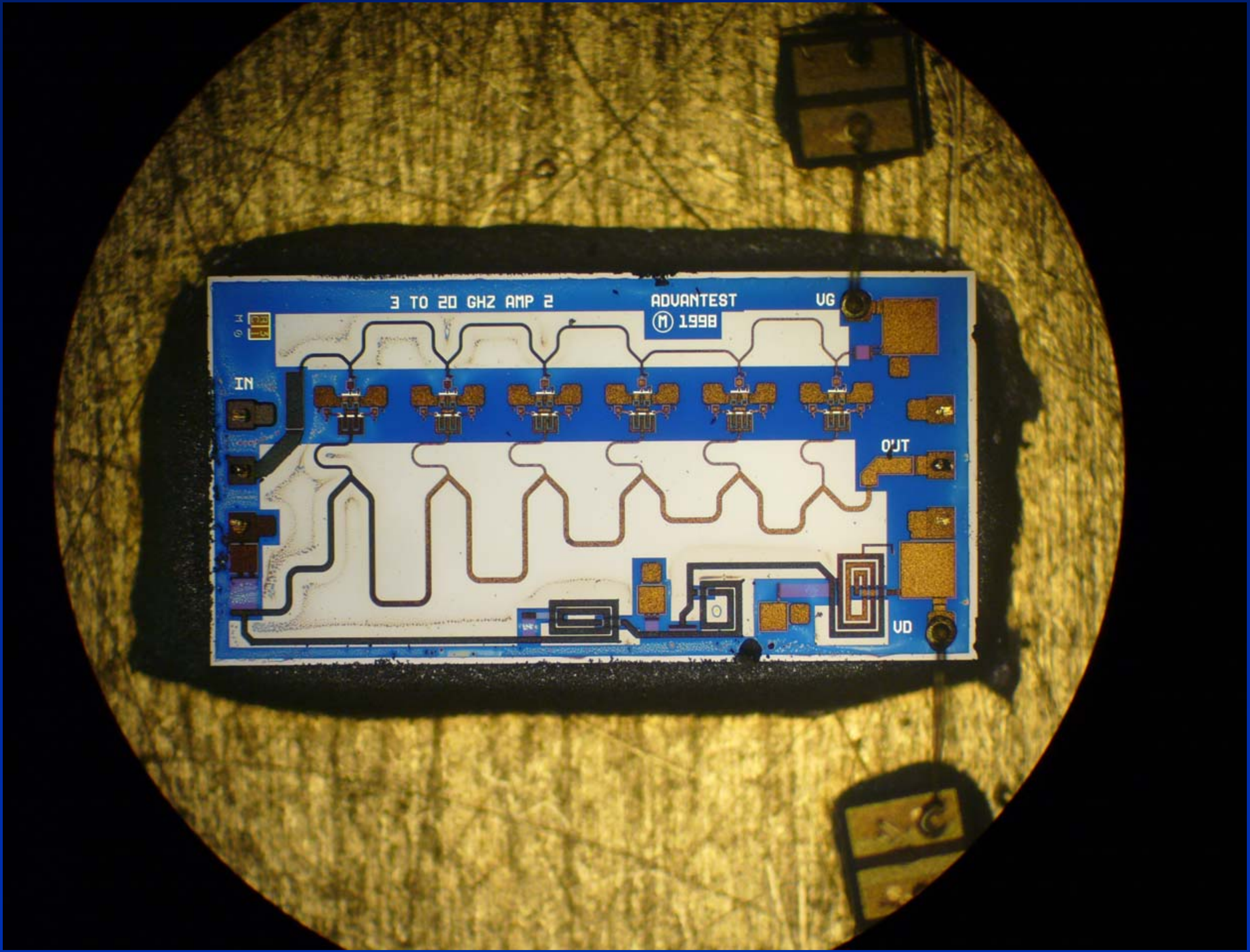


To BB

TX

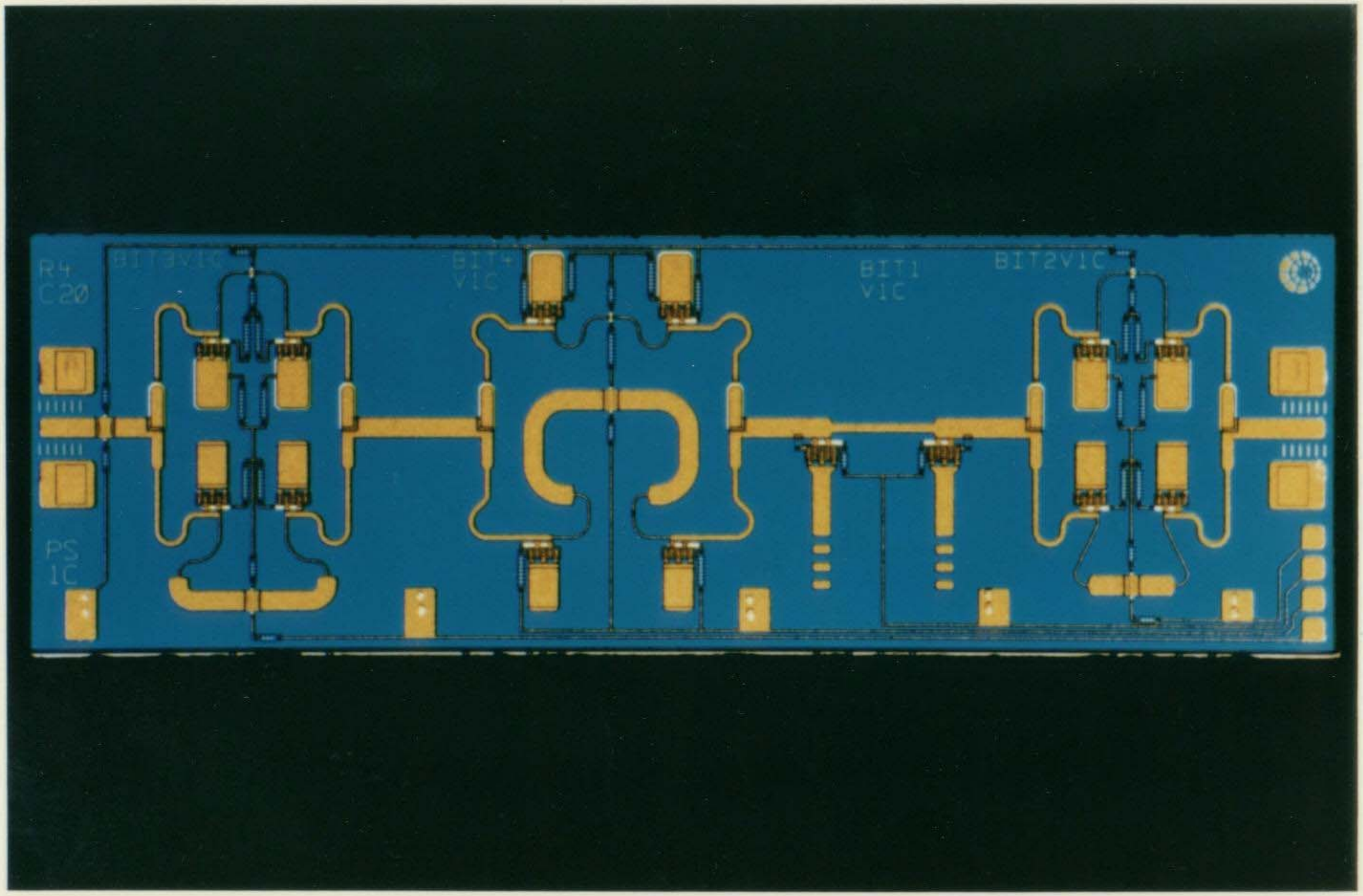
RX

2 – 25GHz Millimeter-wave PA



DC – 40GHz SPDT Switch

44GHz 4-bit Phase Shifter MMIC



Conclusion and Future Trends

- GaAs MMICs dominate power, low noise and passive applications at microwave and will continue to do so in the near future
- Improvements in power levels & efficiency will continue to happen for pHEMT and HBT GaAs MMIC
- BiCMOS & SiGe MMIC is maturing for SOC and RF front end applications
- GaN MMIC are expected to mature in few years and may fulfill the need for 10W to 100W power levels up to mm-waves.
- SiC and LDMOS Silicon MMIC will continue to serve applications for >10W below 5GHz
- High power mm-wave MMICs will necessitate flip-chip designs
- 3-D MMICs will mature for mm-waves and higher level of integration in Silicon.