Materials-Device Correlation Activities

DARPA/MTO 2001 Wide Bandgap Semiconductor Technology Initiative Day

5 Sep 01

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Overview

- Some general comments
- Context of correlation activities
  - Historical
    - Previously successful MIMIC Task 4E
      - GaAs Program as a model
  - Tri-service investigation of degradation

Caveat

The purpose of this briefing is *not* to direct your effort!

Overarching Objectives

- Generally, material/device correlation tasks can have three broad objectives

  (1) Resolve the quality of the material

  - Defects – nature & density

  (2) Render clear picture of suitability of a material for the intended device performance

  - Substrate & material epi design

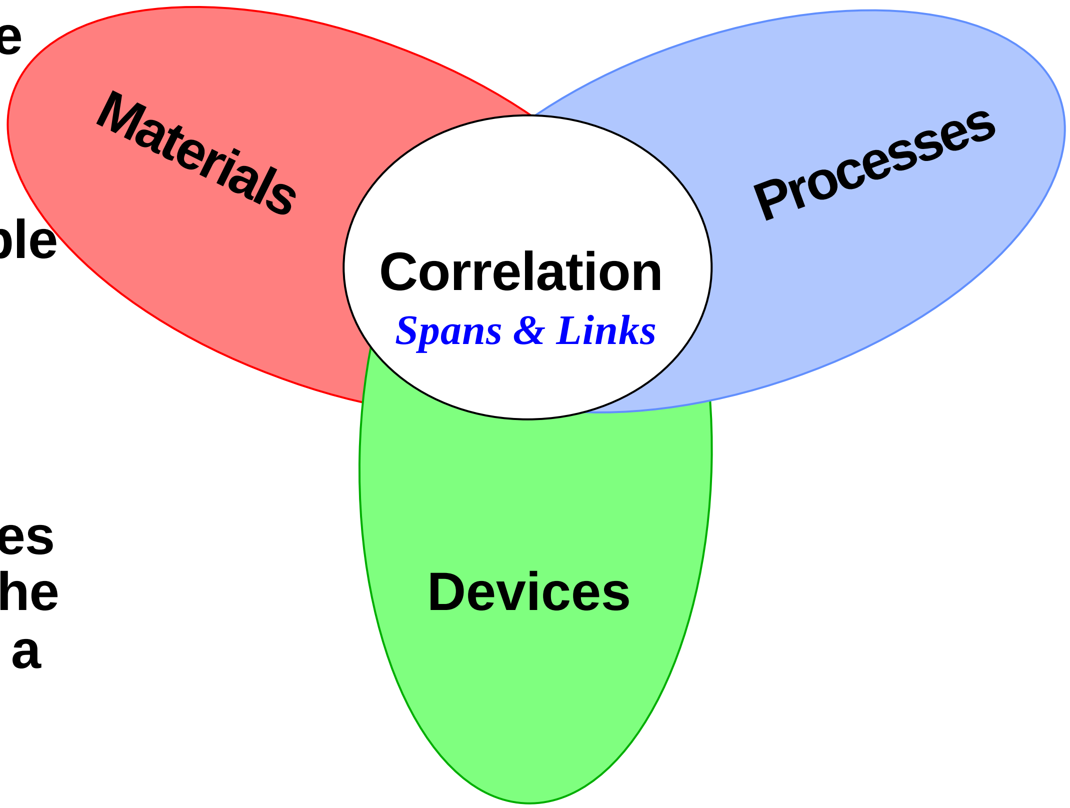
  (3) Determine the impact of materials on yield

  - Tolerances & extent of control

- Enable the additional capability to distinguish among local and global problems

Utility of Correlation

- **Utility is driven by…**
  - **Must identify appropriate parameters to track**
  - **Must be able to link parameters to controllable inputs**
  - **Must have standards & commonalities**
- **Pulling it all together, enables physical understanding of the interrelationships – it is not a “grab bag” of numbers to blindly do statistics – physically based DOE**



Context of Task 1.4

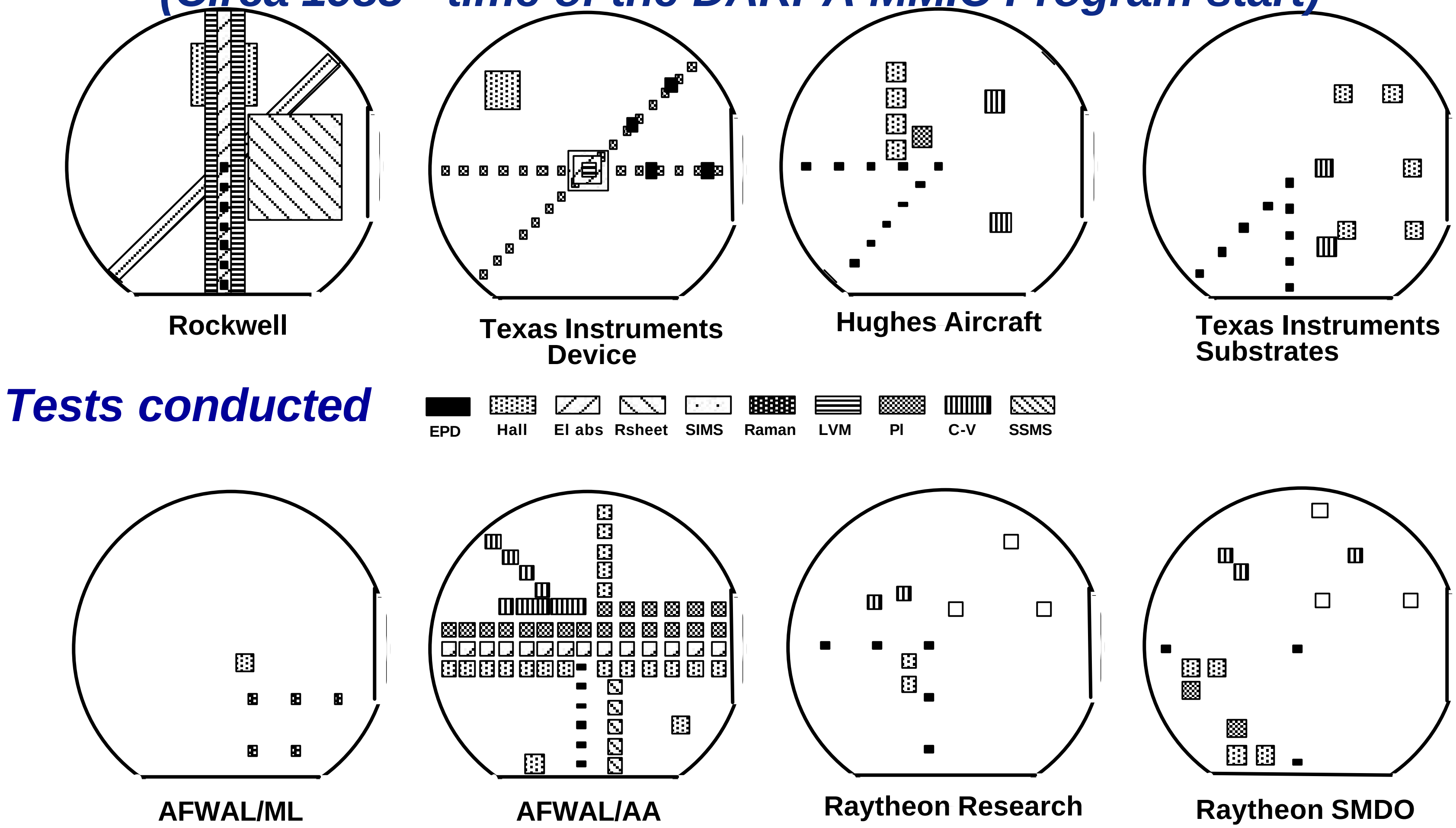
- **Historical context**
  - **GaAs-based MMICs**
  - **Task 4E of the DARPA MIMIC Program & GaAs Materials/Device Correlation Program**
- **Complementary Correlation Activities**
  - **Tri-Service Investigation of Degradation**

Previous Task 4E

- **During DARPA's Previous GaAs-MMIC Efforts in the 90's…**
  - **Found that assessing progress was extremely thorny issue**
    - ***Hard to differentiate changes/improvements*; materials *vs* device design *vs* process *vs* test methods hard to separate**
    - **Adopted AFRL's Materials/Device Correlation Program**
  - **Integrated the use of DoD-provided High Density Test Reticles within company-unique & process-specific mask sets**
    - ***Didn't replace – augmented contractors' PCMs***
  - **Defined task within the DARPA MIMIC Program**
    - **Called "Task 4E"**
    - **Involvement of gov't labs in wafer testing & data analysis assured *commonality & equal assessment***
    - **Correlations provided unique insights into substrate preparation, processing, test technology, and device/circuit design & modeling approaches**

Why Standards?
GaAs Substrate Characterization

(Circa 1985 - time of the DARPA MMIC Program start)



Size and Location of Substrate Measurements from eight different Organizations.

This led to 4 to 1 variation in the reported value of substrate mobility.

From Air Force GaAs Material/Device Correlation Program 1985

GaAs Correlation Program
Material and Analysis Flow

Analysis Flow

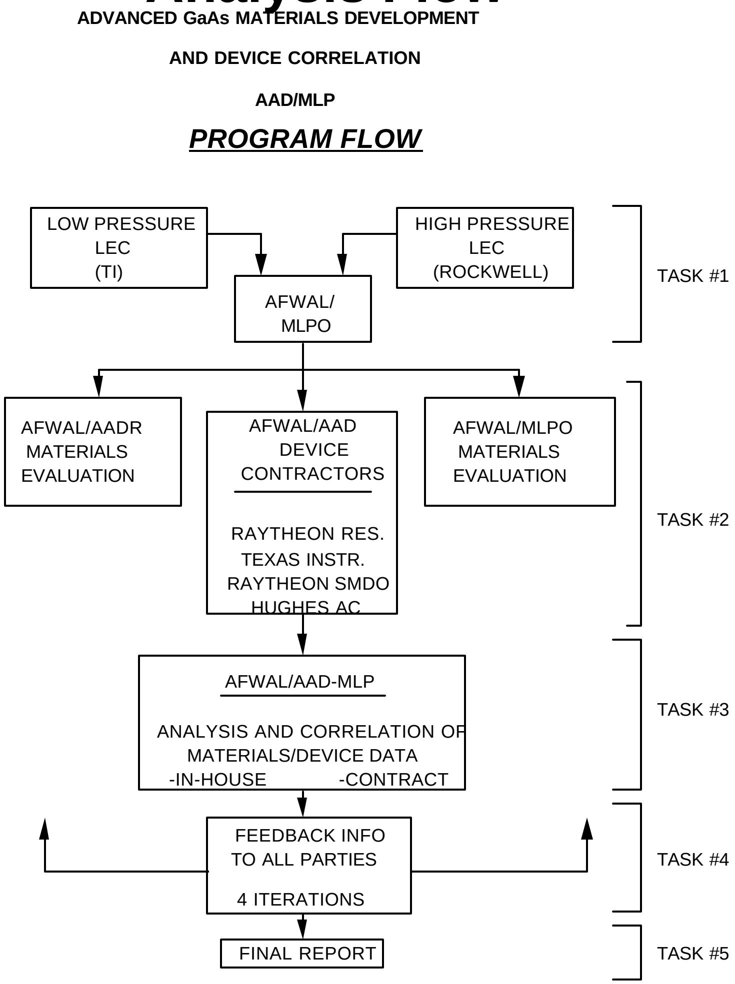


Figure 1-1 Program Organization and Flow

Wafer Distribution

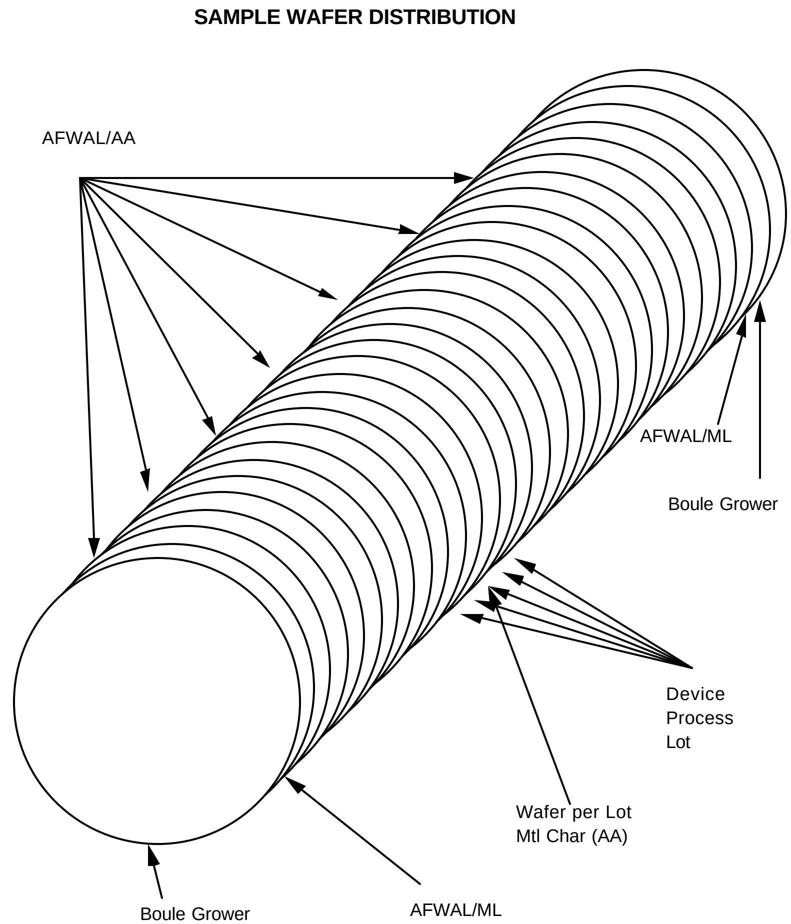
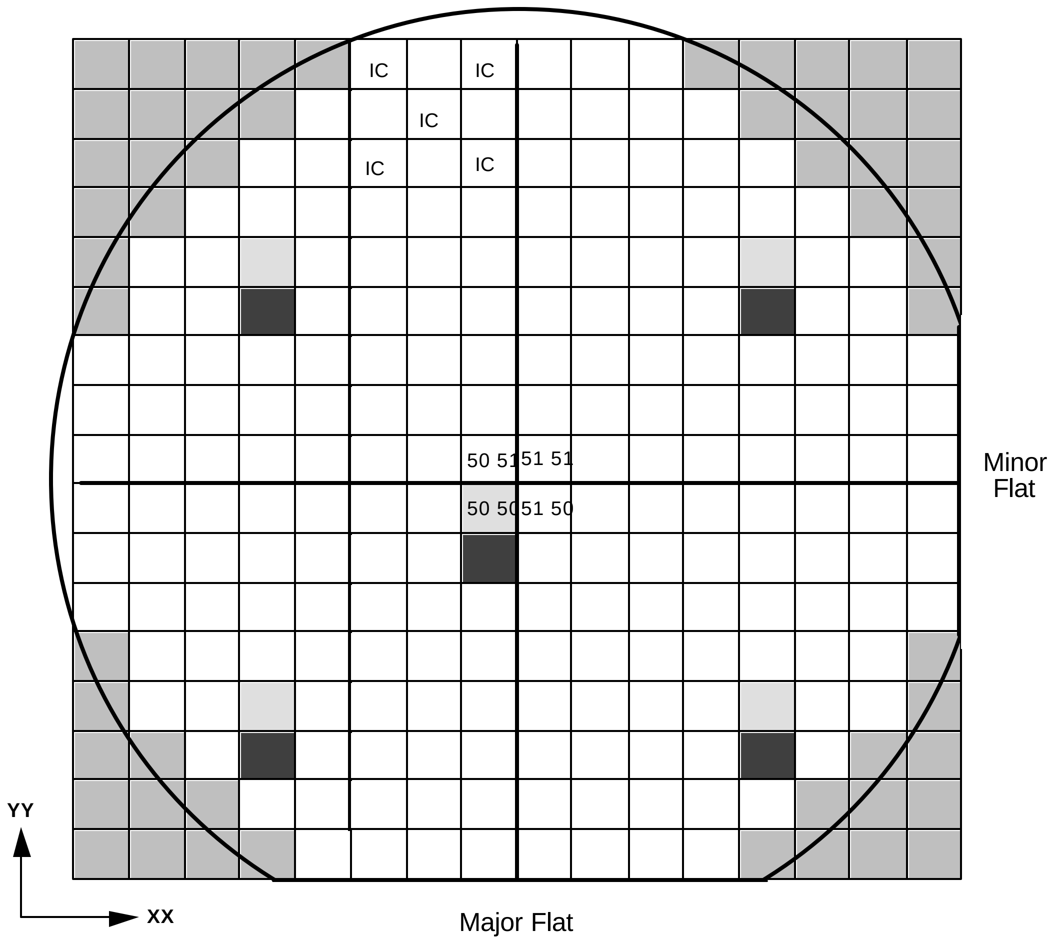


Figure 1-2 Example of Wafer Distribution

Mapping Strategy Used for GaAs

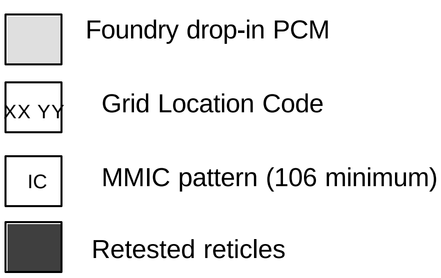
How standards in test structures and test procedures might be applied

Overlay of 3 inch wafer on Grid of Reticles

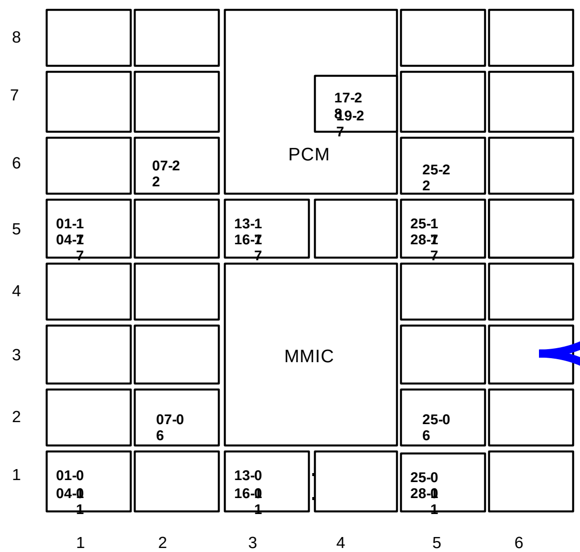


Reticle size = 4.5 mm x 4 mm

218 reticles per 3" wafer



GaAs Correlation Program
Test Reticle - Sub-section



Reticle

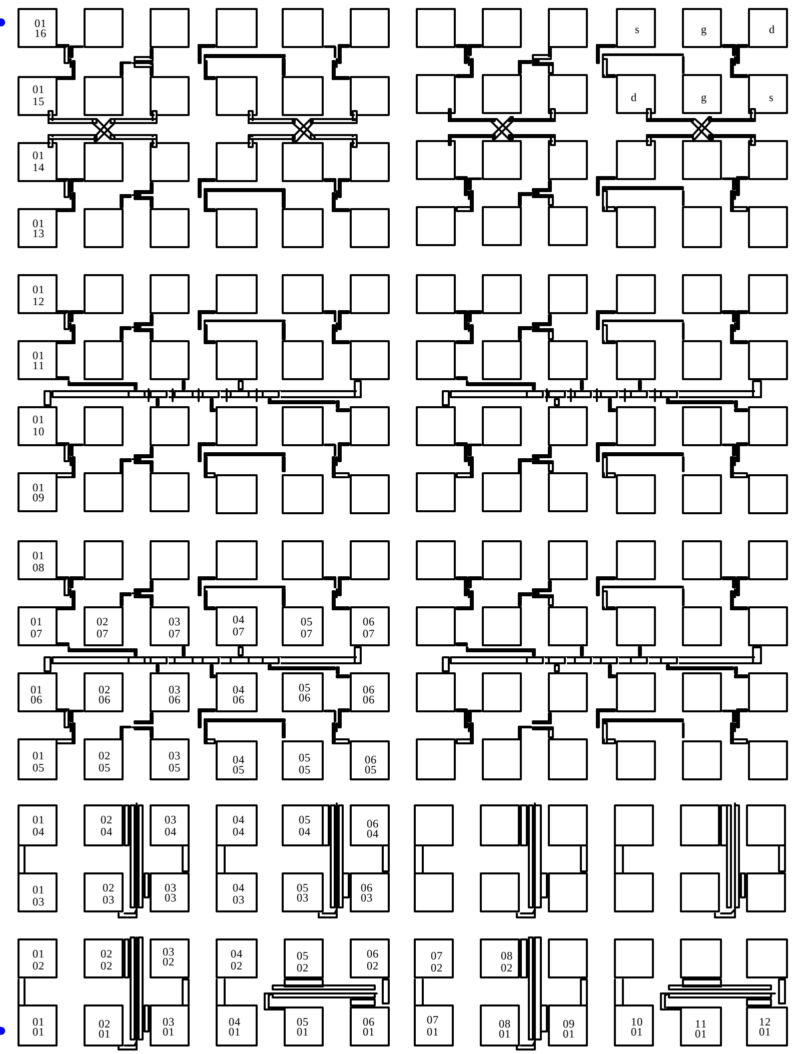


Figure 9-4 Enlarged Lower-left Section of AF Modified HMC Reticle Illustrating Test Structure Arrangement and Pad Numbering Scheme

Van der Pauw

TLM

TLM alt

Vertical and Horizontal FETs

Reticle Section

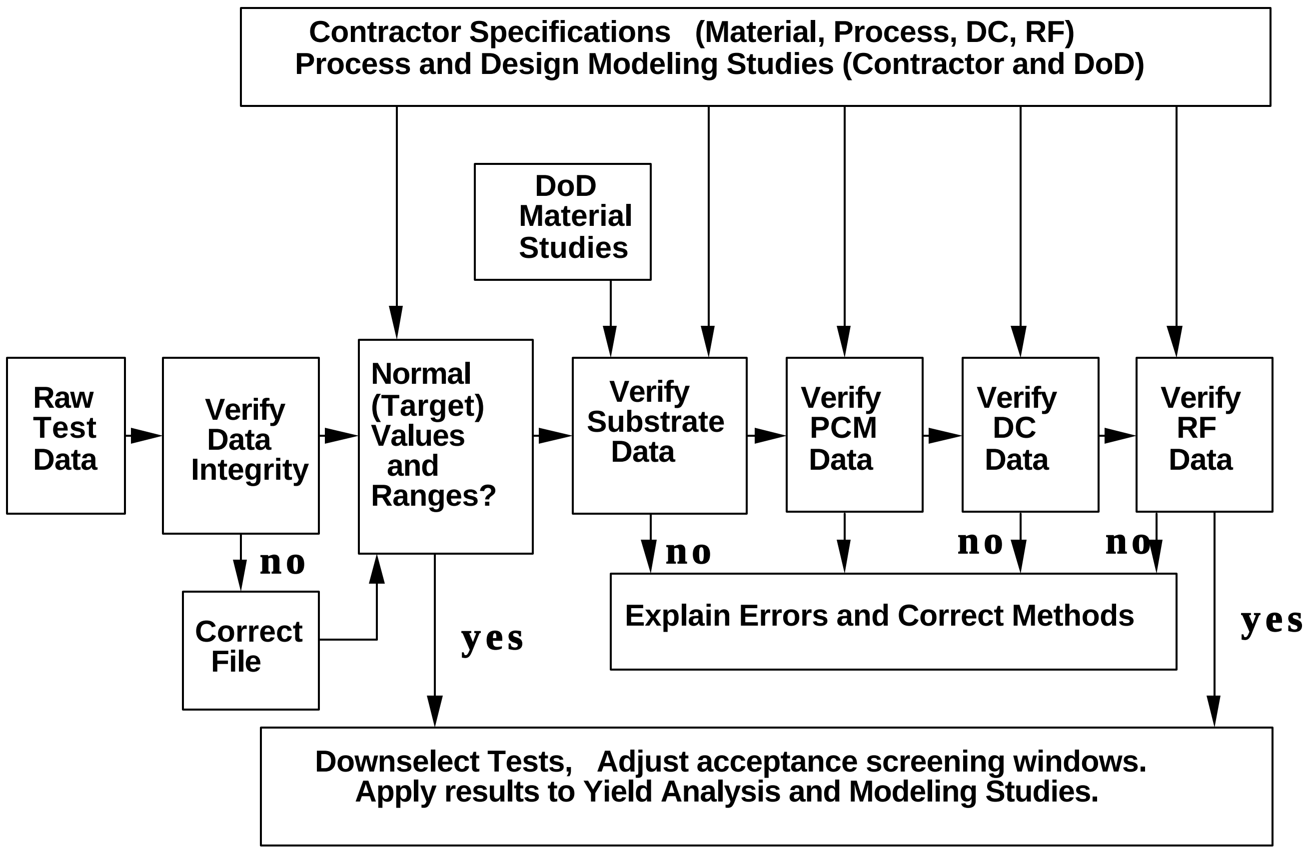
GaAs Correlation Program

DC and RF Specifications

Company/Char	EL	HU	RR	ITT	TRW	GE	TI
Post-gate					#61H	#19H	
Idss (mA/mm)	350/329	300/260/259(cal)	170/252/245	N/A	250/206/186.1	300/258/285	259/246/257
Gm (mS/mm)	?/116.9	110/111/104	150/?/156	N/A	105/106/103.8	90/112/81	218/152/197
Vpo (V)	~3.0/3.03	3.5/3.4/3.4 (cal)	1.5/2.06/2.05 (cal)	N/A	2.2/1.96/2.23	4.5/3.81/3.6	1.54/1.55/1.7
Rds (? -mm)		?/1.55/3.06	?/1.79/3.4	N/A	?/(1.63)/3.03	4.7/?/3.92	?/2.14/2.68
Rgs (? -mm)		2.3/1.94/1.92	?/?/BM	N/A	?/(3.34)/16.16(BM	?/?/2.5	2.5/?/4.0
Rs (? -mm)	0.85/1.34	0.9/.61/2.4BM	?/2.57/1.48	N/A	?/.35/1.06	1.7/1.8/5.4	1.02/.85/.84
Rdg (? -mm)		?/2.11/1.55	?/?/BM	N/A	?/(3.34)/17.96(BM	?/?/2.97	2.5/?/4.1
Rd (? -mm)	.95/1.37	0.9/.778/BM	?/2.57/1.34	N/A	?/.35/1.24	2.2/2.07/2.98	1.02/.85/1.1
Vsat (V)	0.85, 0.88	?/.8/.83	?/.38/.41	N/A	0.8/.45/1.09	?/?/1.28	?/?/.8
Vrdg (v)		?/16.6/20.2		N/A	?/10.6/12.37	15.6/15.4/18.4	17/7.9/BM
Vrsg (V)		?/?/26.2		N/A	?/10.6/12.09	?/15.4/18.4	17.3/7.9/BM
Final DC		#30V	#46H	#63V, 8-24	#61H, 8-22	#19H	
'as Comp (e.g.Si3N4	Si3N4	Si3N4	Si3N4	Si3N4	Si3N4 .19µm		Si3N4
(density, Dx, stress	0.3µm		.2µm,300pF/mm	.3,er=7.3			.2µm
Idss (mA/mm)	250/315	300/237/264/257	170/216/215/219	70/150/158/15	250/206/187.3/174	300/258/299/305	227/246/238/267
Gm (mS/mm)	120/113.6	110/113/106/80.5	150/124/133.8/127	80/143/228/22	105/106/113.3/115	85/112/77/82.9	208/152/200/195
Vpo (V)	~-2.0/-3.05	3.5/3.4/3.4/3.39	1.5/1.7/1.95/1.93	0.94/1.15/.83/.8	2.2/1.96/2.08/2.0	4.5/3.8/3.8/3.8	1.54/1.55/1.52/1.6
Rds (? -mm)	4.6, 3.16	2.3/2.27/2.84/2.89	3.5/?/3.84/3.7	4.5/(3.9)/4.3	?/(1.66)/2.48/2.55	4.7/?/4.16/3.95	?/?/2.53/254
Rgs (? -mm)	2.08/1.88	0.9/(1.94)/1.96/2.23	10/?/BM/3.96	?/(1.88)	?/(3.34)/13.28/2.7	?/?/2.06/2.2	2.9/?/4.0/4.1
Rs (? -mm)	.95, 1.34	?/1.84/1.85/0.91	1.3/0.7/1.71/1.67	.6?/.31/?/.81	?/.35/0.86/.87	1.7/1.8/4.7/1.6	1.15/.85/1.04/1.07
Rdg (? -mm)	2.08/1.79	0.9/(2.11)/1.6/2.72	10/?/BM/3.83	?/(3.8)	?/(3.34)/13.42/2.68	?/?/3.23/2.6	2.9/?/4.0/3.98
Rd (? -mm)	.95/1.26	?/2.66/BM/1.40	1.3/0.7/1.58/1.57	2.0?/.97/?/3.1	?/.35/0.89/.85	2.2/2.07/2.55/1.96	1.15/.85/.97/.99
Vsat (V)	.85/1.1	?/0.8/.84/.889	?/.38/.41/.96	.7/(0.63)/?/.78	.8/.45/1.06/1.1	?/?/1.63/1.34	?/.9/.8/.6
Vrdg	9.1/7.38	?/16.6/19.3/28.5	7.5/8.1/9.47/9.12	9.9/18.2n-/17/3	?/10.6/9.68/9.4	18/15.4/30/24.4	15.3/7.9/9.5/9.6
Vrgs	9.1/6.58	?/?/27.5/22.0	7.5/8.1/9.25/8.7	.5/4.8n+/5.8/7.	?/10.6/9.31/9.7	18/?/19/20.0	15.3/7.9/17.1/14.3
On-wafer RF	#90V	T = 1500 FET	#46V	= (300µm PCM	#61H (15%Idss)	#4-01H	#67V
Vgsrf (V)	1.29	?/1.44/1.87/1.34	?/1.3/1.62/1.62	.35/(.7)/.34/.30	1.0/1.68/1.45/1.45	?/1.5/1.72	0.95/1.28/1.1/1.1
Vds (V)	2.5	2.5	2.5	2.5	2.5	?/2.5/2.5	2.5
Idsrf (mA/mm)	165	7.5/120/150.5/138.	50	80/75/70/76	125/30/27.5/28	?/127/137	50
gmrf extr.(mS/mm)	109.7	70/64.3/1.59/55	?/93/92.3/93.7	65/143/155/15	105/58.5/55.1/54.3	?/67.8/65.48	173.3/109/127/134.7
gmrf intr (mS/mm)	129.3	?/65/1.59/60	?/100/112/113	?/150/186/185	?/59/59.2/58.1	?/69.2/76.88	?/116/156/163
Rs (? -mm)	1.159	0.4/1.84/.21/1.0	?/.7/1.4/1.32	.5/.31/.81/.702	2.5/.35/.86/.84	?/1.8/1.57	1.12/.85/1.0/.97
Rd (? -mm)	1.166	0.75/2.66/-.28/1.25	?/.7/1.48/1.43	0.7/.97/3.1/2.80	4.2/.35/.85/.75	?/2/2.04	1.12/.85/.97/.93
Rg (?)	2.75	0.65/?/.5/.5	?/10.7/11.8/11.8	5/5.55/?/5.08	4.2/4.5/4.2/9.3rf	?/5.08/2.12	?/16.9/17.2/13.7
Rdsrf (? -mm)	81.35	213/496/60.7/76.47	?/104/70.5/72.5	20/225/132/13	76/160/53.2/53.2	?/?/116.9	?/53/71.9/66.7
Ri (? -mm)	0.88	5.75/3.14/4.99/BM	?/2.4/1.8/3.76	0.7/.85/.42?/.52	.39/3.05/2.85/1.1	?/4.15/1.706	?/2.23/2.2/2.25
Cds (pF/mm)	0.24	.183/.112/.215/.20	?/.11/.27/.24	.23/.11/.22/.23	0.22/.12/.317/.324	?/0.028.257	.15/.11/.27/.27
Cgd (pF/mm)	0.142	0.083/.055/.05/.07	?/.085/.18/.17	0.07/.1/.1/.09	0.10/.085/.165/.16	?/0.016/.087	.12/.07/.13/.13
Cgs (pF/mm)	1.394	.722/0.455/.045/.6	?/.6/.68/.69	.7/.63/1.54/1.5	0.79/.37/.56/.61	?/0.137/1.15	1.1/.55/.91/.85
tr (†) (psec)	2.84	6/3.4/5.98/BM	?/3.17/2.45/1.6	.5/3.33/2.9/3.2	3.5/3.1/1.01/2.2	?/3.14/3.99	0.67/3.1/2.5/1.8
Ft (GHz)	13.45	?/22.4/BM/12.6	?/23.6/20.6/20.7	?/36.2/18/?	?/28.5/12.9/11.9	?/15.78/10.06	?/30/26/24
MMIC Gain (dB)							
NF (dB)	2.5		?/1.54/?/.9	?/1.34/?/?	?/1.4/?/?		?/1.55/1.5/1.3

GaAs Correlation Program
Data Screening and Verification

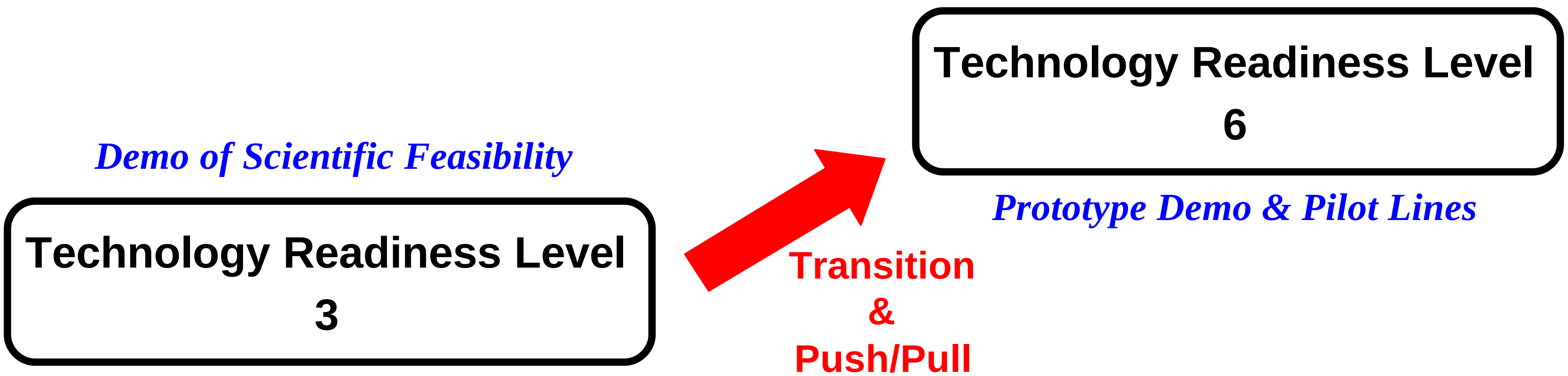
GaAs Material/Device Correlation Program
Data Analysis Flow



Evolved and Idealized Flow Diagram for Data Screening and Analysis

Tri-Service Degradation Investigation

- **Focus is on nitride-based microwave power devices**
- **Separate from and complements the DARPA Wide Bandgap Semiconductor Technology Initiative**
- **Will use a *correlation approach* to baseline and to explore various developments' impact on fundamental degradation mechanisms**
  - **One tool to advance the readiness of nitride electronics**



Pillars of Assurance for GaN

Performance

Very promising results have been demonstrated

–**Do we understand and control the degradation mechanisms?**

–**Will a *reliable* nitride device produce the *revolutionary* RF performance?**

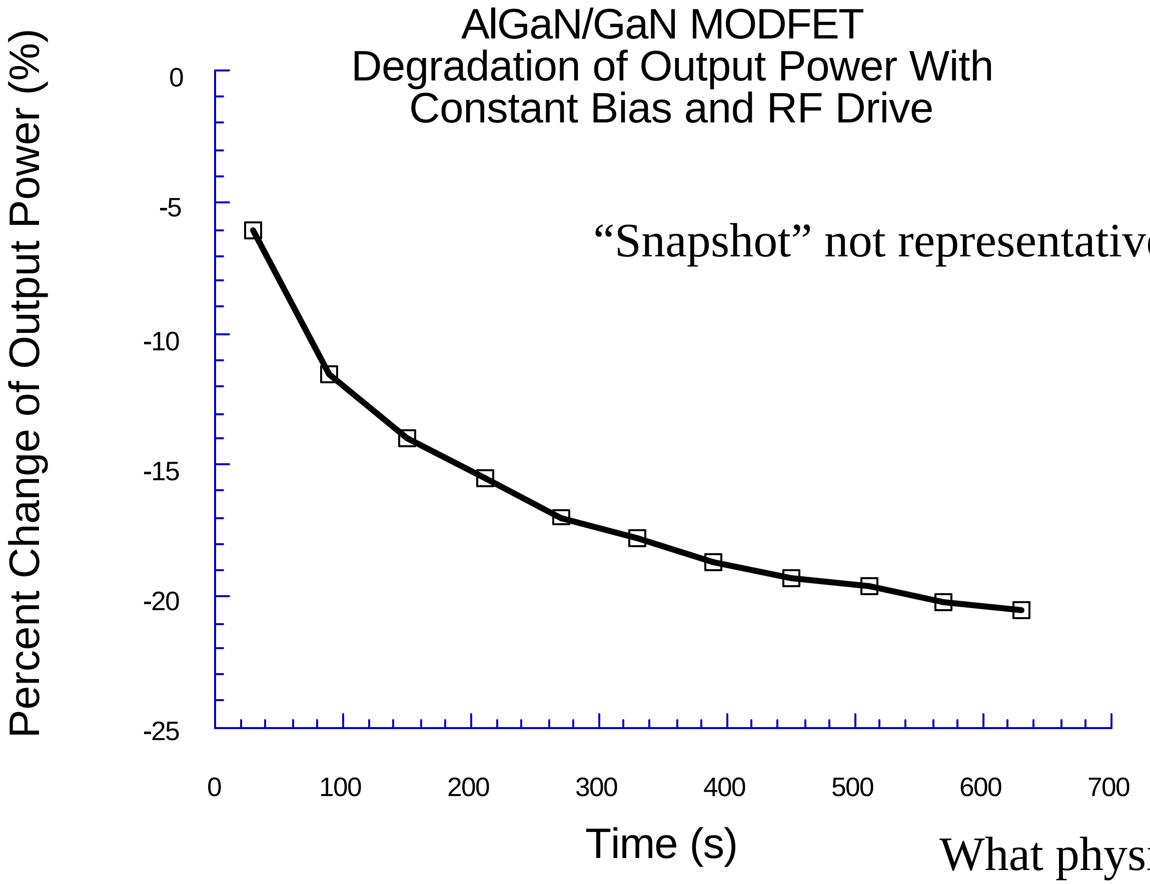
Reliability

Availability

Stability - without Degradation or early Failure is needed.

•Infrastructure, Market forces- Mfg. - volume, yield & cost.

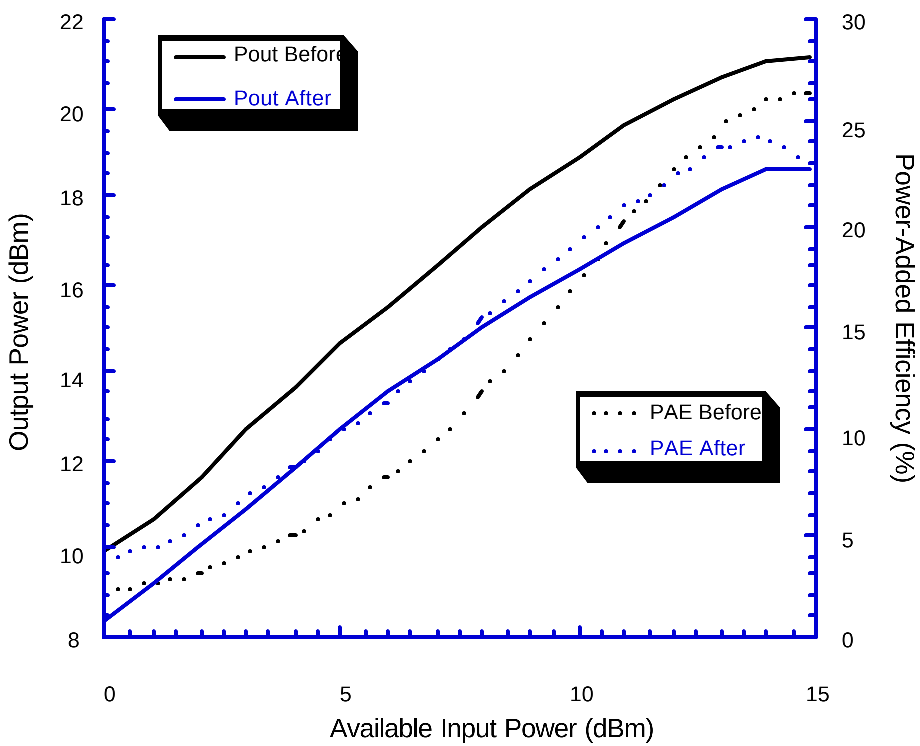
Example of Degradation

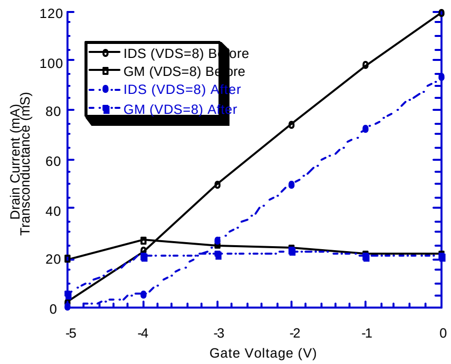


"Snapshot" not representative of ***all*** devices.

What physical mechanism?
What physical model?
What cause/effect?

Stress Test





RF & DC Changes

After short RF/DC stress

(Not same device as previous chart)

Seen by all participants and viewed as a real problem

Now is the right time to tackle with an appropriately scoped effort

Workshop on Nitride Electronics Degradation

- **Held at Wright-Patterson AFB on 9 May 01**
- **Representatives from industry, academia, and gov't (spanning from materials to circuits)**
- **Determine the scope of the problem and merit of investigating degradation at this stage of nitride development**
- **Initiate effort to formulate a program to advance nitride readiness**
- **Follow-up meeting held at NRL on 30 Aug 01**

Focus on Degradation

- **What it is not…**
  - **Not looking to improve power FOMs (density, efficiency, bandwidth, etc.)**
    - **Desire a given power FOM for a period of time**
  - ***Not compiling MTTF's***
- **What it is…**
  - **Investigate those physical mechanisms that produce deleterious changes in performance over a period of time and distinguishing between transient and permanent effects**

General Summary of Degradation Problem

- No standard metric (lack functional definition or common characterization process)
  - Transient & permanent effects were not always clearly separable
  - Broad range of “failure” times (minutes to hours)
- Insufficient data to draw conclusions concerning mechanisms or to confidently estimate “reliability”
- Strong, virtually unanimous consensus that degradation is a problem that must be investigated starting now - the question is: How to best proceed?
- Scope of problem may be too large for any one company or organization to address

Consensus On
The Problem & Needs

- Need to refocus the “energy” of the community towards reliability, reproducibility, and uniformity - not just performance FOMs
- Start to correlate device results to starting material with better feedback to growers
  - Rapid feedback of device results to growers with closer interaction between device processors and material growers
  - Not just data correlation for correlation’s sake, but apply strategy to process
    - Select properties relevant to RF performance
- Develop improved physics-based device models
- Need to understand the mechanisms
  - Those producing the degradation
  - Separating and addressing permanent & transient time-dependent performance

Consensus On The Problem & Needs (cont'd)

- **Develop substrate specifications**
- **Stabilize wafer properties (Iterative process addressing macro-properties)**
- **Must distinguish between material-related effects and process-related effects (not trivial)**
- **Develop standard process control monitors**
  - **Structures & layout of PCM**
  - **Test process and test conditions**
- **Develop standard characterization and testing conditions for degradation/reliability**
  - **Defined, in part, by MIL requirements**
  - **Devices (RF stress, conditions - temp, bias, power level, etc.)**
  - **Materials (standard techniques)**
- **Need for gov't "clearing house" function**
- **Follow-up meeting to structure a Tri-Service approach to a correlation program**

Conclusions From Gov't-Only Caucus

- Follow-up meeting to structure a Tri-Service approach to a correlation-like program
- Initially focus on "Phase Zero" effort with 3 general areas of interest
  - Identify material defects that directly impact RF device degradation
    - Identify & develop associated testing/characterization techniques (destructive & nondestructive with sufficient resolution)
  - Develop a common testing and measurement standards
    - Need standard/common techniques to correctly interpret data from multiple sources
  - Develop a common RF device mask to allow more rigorous correlation efforts

First baseline where the technology is with a snapshot using meaningful data

Summary

- I’m not directing!
- Correlation activities link materials and devices
  – Provides feedback and demonstrates the physical basis of the interrelationships of materials, processing, and devices
- Expected to quantify the degree to which the improvements in materials will enable realization of the desired high-performance devices and integrated circuits
- Correlation was used in previous programs with success
  – Task 4E
- Correlation activities complement other initiatives
- Requires a well defined plan, careful execution, and teaming