INTRINSIC UNMANUFACTURABILITY IN NANOELECTRONICS

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Volume Manufacturability Requires

• Superior and pre-specified performance, reproducibility, uniformity, reliability, narrow performance spread.

• High yield to acceptable tolerance AND right-first-time design capability.

• Simulator for both reverse engineering during development and right-first-time design.
Some Limits on Manufactured Device Performance

• Physics limits: $e$, $h$, $m_e$, $c$, …

• Device operation limits — set by materials — the Johnson criteria

$$V_M f_M = \left( E_B v_s \right)/2\pi, \quad PZ(f_M)^2 = \left( E_B v_s \right)^2/32\pi^2$$

$E_B$ = dielectric breakdown field, $v_s$ = Saturated drift velocity, $V_M$ = max. bias, $f_M$ = max frequency, Power $P$ into Load $Z$

• Fabrication limits: set by ratios: $\lambda/a$, $m_e/M$, $kT/E_{bind}$, $E_{RF}/E_{bind}$

(Not nicely formulated)
Low dimensional semiconductor devices

• 3D→2D transition: almost unalloyed good news
  - new physics
  - new devices
  - same technology

• 2D→1D→0D: not as successful
  - much new physics
  - few new devices,
  - none in volume production
  - are they intrinsically unmanufacturable?
Heterojunction Devices: Commercial Successes

(b) Hot electron injection
   Gunn Diode
   HBT

(c) Quantum confinement
   HEMT

(d) Quantum confinement
   QW Laser

(e)/(f) Tunnel devices

(g) Inter-subband absorption
   QWIR detectors

$=\text{big business}$

$$=\text{very big business}$

Figure 1. Physics of multi-layer semiconductor structures, showing (a) generic energy band diagram at a single heterojunction; and principles of: (b), hot electron injection; (c), quantum confinement and formation of a two-dimensional electron gas at a heterojunction; (d), quantum confinement within a quantum well; (e), tunnelling through a thin barrier; (f), resonant tunnelling in a double barrier structure; (g), inter-sub-band absorption in a quantum well; and (h) the band gap line-ups in more exotic materials, e.g. GaSb/InAs. The thicknesses of key layers are of order 3–20 nm for quantum phenomena to be realized.
Heterojunction Gunn Diode

Insert a graded AlGaAs layer plus n+ spike at the cathode of an n+-n-n+n+ Gunn diode – injects hot electrons into the transit region.

Doubles output power and efficiency over the 35-100GHz range – >100mW at 94GHz.

InP power from GaAs device!

Temperature dependence of output power reduced by factor of 4 over the -50C to +80C temperature range.

Single sideband noise level reduced by a factor of 10.


Fig. 1. Schematic diagram of our injector structure as bias is applied: (a) zero bias, (b) ~ 0.1 V, at which point the n+ spike is just fully depleted, and (c) for bias >0.1 V (here 0.25 V) where the depletion region extends into the drift region, just as in a conventional n+-n-n+n+ Gunn diode.
Family of Microwave Detectors

Thermionic emission (T-sensitive) versus Tunnelling (T-insensitive)

Schottky diode

Backward diode

Planar-doped-barrier (PDB) diode

Asymmetric SPACer-layer Tunnel (ASPAT) diode
ASPAT Diode as Detector

(a) Schematic diagram of the ASPAT diode with doping profiles.

(b) A graph showing the transfer efficiency of the ASPAT diode.

(c) A graph illustrating the relative change in performance with temperature.

(d) Comparison of ASPAT, PDB, Schottky, and Ge diodes.
Extreme sensitivity to barrier thickness and height.

Figure 2. The sensitivity of the d.c. characteristics to (a) monolayer differences in layer thickness, and percentage shortfalls in the aluminium composition, and to (b) the position of the doping profile and the doping level in the intermediate layers.
Pushing metrology to its limits

Figure 3. The radial uniformity of the MOCVD samples as implied by TEM (circles), SIMS (squares) and XRD data (triangles) for (a) the thickness of the GaAs layers above the AlAs barrier layer, (b) the thickness of AlAs barrier layer itself from TEM (with the range of locally measured values indicated), and (c) the doping level in the contact layers from SIMS. It appears that all layers are systematically thinner than the target specification. The data marked by open symbols are from wafer epi#4 and by full symbols from epi#5.

Figure 4. The radial uniformity of the MBE samples as implied by TEM (circles), SIMS (squares) and XRD data (triangles) for (a) the thickness of the GaAs layers above the AlAs barrier layer (b) the thickness of AlAs barrier layer itself from TEM (with the range of locally measured values indicated) and (c) the doping level in the contact layers from SIMS. The data marked by open symbols are from wafer GB1355 and by full symbols from GB1358.
1st Iteration Comparison: MBE vs MOCVD

MBE layer 0.5 monolayer too thick.

MOCVD layer nearly one monolayer too thin.

Factor of >3 difference in current, all down to 1 monolayer.

*Figure 7.* A direct comparison of the current density from larger-area diodes made from MBE and MOCVD material grown to the same specification.
Wafer Map of DC I-V Characteristics

Ex-situ calibration

Layers grown a month apart

Open symbols: Calibration of barrier

Filled symbols: Calibration of both barrier and doping

Figure 4. Current densities at 0.4 V for devices from wafers A (□), B (○) and C (△) (open symbols) of the first series, and from wafers D (■), E (●) and F (▲) (filled symbols) of the second series, all shown as a function of radial position on the wafer. Note the improved reproducibility achieved during the second series.
Detailed microstructure of each interface at 10nm scale determines the tunnelling.
Tunnel devices: a summary

- Can achieve required uniformity (wafer D)
- Wafer to wafer uniformity still not adequate
- Wafer to wafer reproducibility still unacceptable
- Is there something of a thermodynamic limit preventing further progress?
- Are integer layer thicknesses any hope?
- Another new idea being pursued at present.
But 1D Transport Phenomena

- No commercial devices after 20 years of R&D.
- Defect in 1D = open or short circuit
- Statistical fluctuations along length localise carriers.
- R.M.S. deviation in cross section area along the length is critical.
- Doped 1D semiconductor structures have limits set by effective Bohr radius
- Aligned carbon nanotubes not yet manufacturable – need 12” wafer of aligned nanotubes to start!

Figure 4. Structures for realizing quasi-one-dimensional transport in semiconductor microstructures. In the quantum pillar, addition of semiconductor multi-layers can be used to produce a quantum dot in the middle. Schottky gates of simple and complex topology can be used to induce quasi-one-dimensional structure into a two-dimensional electron gas.
Split-Gate Transistor – Quantum Wires

Possible applications in:

quantum signal processing
quantum metrology

Figure 1. The split-gate transistor: (a) a schematic diagram, (b) a plane view of a typical Hall bar, (c) a SEM image of a typical device and (d) a SEM image of a split-gate transistor, showing the fine E-beam split gates with a 400 nm by 400 nm gap.
Figure 2. Quantized conductance $G(V_g)$ of a split-gate transistor and its derivative.
G-V data at 1.4K – data from 15 groups of 36 transistors

1\textsuperscript{st} and 2\textsuperscript{nd} plateaux are reproducible – the threshold varies widely. Beginning work on a quantum multiplexer.
Split Gates a summary

• ‘Intrinsically’ unmanufacturable
• Yield 60% at best and
  – increases with mobility
  – optimum at optimum growth temperature
  – increases with illumination
  – variability increases with illumination
• Low temperature contact technology
Quantum Dots (1)

Many publications,
All showing $\sigma / v = 15\%$

QD lasers not widespread

Zhang et al APL 86 191103 (2005)

FIG. 1. (Color online) Atomic force microscopy image of a single layer of InAs quantum dots on the GaAs/InP matrix. The scan shows a dot density of about $4 \times 10^{10}$ cm$^{-2}$. 
Quantum Dots (2)

• Spread in volume ⇒ spread in energies ⇒ too wide a distribution for all dots to contribute to narrow-line optical effects.

• We need to get the volume distribution to less than 5% for 5nm quantum dots: less than one monolayer on each side!

• More efficient lasers need more dots and much narrower spread of volumes.

• Or, need spread that is reproducible to the equivalent level. Low cost modulators.
What about the possibility of intrinsic unmanufacturability?
(i) 3nm half-pitch array intrinsically unmanufacturable

- Array of quantum pillars of 3nm diameter on 6nm pitch
  - 80 atoms per base layer
  - $1/\sqrt{N} = 12\%$; $3\sigma = 36\%$
  - Unacceptably broad optical spectrum
  - If filled in with tunnel barriers, transport well within Anderson disordered regime
  - Cannot wire-up to address, store or read out with any fidelity
- Quantum wires of 3nm cross-section
  - $1/\sqrt{N} = 10\%$; $3\sigma = 30\%$
  - Well within Anderson disordered transport regime
(ii) Small transistors

- Gate dielectric of 10nm transistor:
  - 30 atoms on end and ± one atomic layer error on perimeter is ±6% in area.
  - 1000 atoms per monolayer, and only a few monolayers, $1/\sqrt{1000} \approx 30$ or 3% intrinsic statistical variation in dielectric properties.
  - Atomic Layer Epitaxy an exception
  - Together these imply $\sigma=\sim 9-10\%$
  - ITRS has $3\sigma<12\%$ for today’s devices.
  - $6\sigma = 3.4$ defects per million impossible at 10nm
(iii) Quantum Dots and Nano-floating Gates

- Since 1990, r.m.s. deviation of quantum dot size is 15% by volume for 5nm diameter quantum dot
- Equivalent to ± one atomic layer on outer layer
- Cubic dot: \( \Delta V/V = (3dr/r) \approx 20\% \) for \( r=5\text{nm} \)
- Hemispherical quantum dot \( (3dr/r) \approx 35\% \) at \( r=5\text{nm} \)
- Quantum confinement energy varies as \( (2dr/r) = 13\% \) and 22\% respectively
- In the absence of any absolute self-limiting step, this 15\% is the fundamental lower limit.
(iv) Implications

- No 1D or 0D quantum scale devices have proven manufacturable
- The real challenge today is manufacturability of quantum scale artefacts
- The practical interface is probably at about 7nm rather than 3nm half-pitch
  - $6\sigma = 10\%$ at 7nm feature size.
  - Cost and technical difficulty ended earlier technologies.
- When Si CMOS runs out of steam, alternatives will not take over
  - Diversity – more than Moore will become dominant
  - Improved software efficiency will improve computing power
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MARINE STEAM TURBINES

- Parson type turbines
- Improved materials/designs
- FOM=shaft HP in MW
- UK except for last two
  - USS Iowa (42)
  - USS Midway (46)
- 40MW not exceeded
- Cost not justified
- Source: Ingar Jung
- ‘The Marine Turbine) in 3 vols (‘86,’86,’86)
  National Maritime Museum
JET PASSENGER AIRCRAFT

- Max cruising speed = v (in km/hr)
- Max no passengers = n
- People mtm=nv/(10^5)
- Boeing data
- 377/707/720/747/747-700…
- Source: Janes Aircraft of the World 1952-2000