The High-Electron Mobility Transistor at 30: Impressive Accomplishments and Exciting Prospects

J. A. del Alamo

Microsystems Technology Laboratories
MIT

International Conference on Compound Semiconductor Manufacturing Technology
May 16-19, 2011
Outline

• Introduction
• HEMT electronics
• Modulation-doped structures in physics
• Future prospects
A New Field-Effect Transistor with Selectively Doped GaAs/n-AlₓGa₁₋ₓAs Heterojunctions

Takashi Mimura, Satoshi Hiyamizu, Toshio Fujii and Kazuo Nanbu

Fujitsu Laboratories Ltd.,
1015, Kamikodanaka, Nakahara-ku, Kawasaki 211
(Received March 24, 1980)

Mimura, JJAPL 1980
Energy band diagrams in Mimura’s patent application (Aug. 16, 1979)

Courtesy of Takashi Mimura (Fujitsu)
Modulation doping

- High electron mobility in modulation-doped AlGaAs/GaAs heterostructures
- 2 DEG at AlGaAs/GaAs interface

Dingle, APL 1978

Störmer, Solid St Comm 1979
HEMT by other name...

Thomson-CSF: Two-Dimensional Electron Gas FET (TEGFET)
Laviron, EL 1981

U. Illinois: Modulation-Doped FET (MODFET)
Su, EL 1982

Bell Labs.: Selectively-Doped Heterojunction Transistor (SDHT)
DiLorenzo, IEDM 1982
And the winner is...

Data courtesy of Angie Locknar (MIT Libraries)

# papers in Compendex and Inspec databases with keyword in title, abstract or indexing terms
First HEMT IC

“The switching delay of 17.1 ps is the lowest of all the semiconductor logic technologies reported thus far.”

Mimura, JJAPL 1981

“HEMT technology is presenting new possibilities for high-speed low-power very-large-scale-integration.”
HEMT ICs ride Moore’s Law

1984: 1 Kb SRAM (7,244 HEMTs, 8.7 mm²)
1984: 4 Kb SRAM (26,864 HEMTs, 21 mm²)
1987: 16 Kb SRAM (107,519 HEMTs, 24 mm²)
1991: 64 Kb SRAM (>462,000 HEMTs, 48 mm²)

Watanabe, TED 1987
Suzuki, JSSC 1991
Abe, JSSC 1991
Abe, JVST1987
First HEMT LNA

20 GHz 4-stage HEMT LNA (1983)

Niori, ISSCC 1983

Great improvement in noise characteristics as $T \downarrow$
Early commercial applications

First commercial HEMT product: cryogenic low-noise amplifier at Nobeyama Radio Observatory (1985)

First mass market product: 0.25 μm GaAs HEMTs for LNA in DBS receiver (1987)

Used to discover new interstellar molecule C₆H in Taurus Molecular Cloud (1986)

By 1988, world wide production of HEMT receivers reached 20 million/year

Mimura, JJAP 2005

Mimura, Surf Sci 1990
Delta-doped pseudomorphic HEMT

- Motivation: lower $x$ in Al$_x$Ga$_{1-x}$As to avoid carrier freeze-out
- Enhanced transport in InGaAs
- Large $\Delta E_c \rightarrow$ enhanced current

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Pseudomorphic HEMT

Ketterson, EDL 1985

1. Drain Current ($I_D$) vs. Drain Voltage ($V_D$)
2. Layer Structure:
   - 200 Å n-GaAs
   - 350 Å n-Al$_{0.15}$Ga$_{0.85}$As
   - 30 Å Al$_{0.15}$Ga$_{0.85}$As
   - 200 Å In$_{0.15}$Ga$_{0.85}$As
   - 1 μm GaAs

Delta doping

Chao, IEDM 1987

- Enabled barrier thickness scaling $\rightarrow$ improved transconductance and scalability
- Enhancement of breakdown voltage
PHEMT ICs

UMTS-LTE PA module
Chow, MTT-S 2008

40 Gb/s modulator driver
Carroll, MTT-S 2002

77 GHz transceiver
Tessmann, GaAs IC 1999

Single-chip WLAN MMIC, Morkner, RFIC 2007

Bipolar/E-D PHEMT process
Henderson, Mantech 2007

Single MOCVD growth
HEMT markets

$1.2B expected in 2011

2009 HEMT MMIC market segmentation (Total=$944 M)

• Biggest market: wireless communications
• Biggest applications: cell phone handsets, WLAN, base stations and CATV

Data courtesy of Eric Higham (Strategy Analytics)
HEMTs in other material systems

- **InAlAs/InGaAs on InP**
  - *Si Doped Al$_{0.49}$In$_{0.52}$As (n=1x10$^{17}$ cm$^{-3}$, 0.15 μm)*
  - *Undoped Ga$_{0.47}$In$_{0.53}$As (n=2x10$^{15}$ cm$^{-3}$, 1.5 μm)*
  - *Semi-insulating InP substrate*
  - [Graph of characteristics]

- **SiGe/Si**
  - [Graph of characteristics]

- **AlGaN/GaN**
  - *n-GaN*
  - *AlN*
  - *Sapphire*
  - [Graph of characteristics]

*Also: AlSb/InAs, AlInSb/InSb, etc*

*Chen, EDL 1982*

*Daembkes, TED 1986*

*Khan, APL 1993*
High Hole Mobility Transistors

AlGaAs/GaAs
Si/SiGe
AlSbAs/GaSb

Störmer, APL 1984
Pearsall, EDL 1986
Luo, EDL 1990

Also: AlGaAs/InGaAs, InAlAs/InGaAs, AlGaSb/InGaSb, InGaN/GaN, etc
Complementary HEMT/HHMT ICs

AlGaAs/GaAs system

Also: InAlAs/InGaAs system

Cirillo, IEDM 1985

171,000 transistor 16-channel signal distribution system

Brown, Trans VLSI Syst 1998
**InAlAs/ InGaAs HEMTs on InP**

Uniqueness: very high mobility and velocity

→ record frequency response at very low voltage

\[ f_{\text{avg}} = \sqrt{f_T f_{\text{max}}} \]

\[ f_{\text{max}} = 1.25 \text{ THz} @ 0.8 \text{ V} \]

Kim, IEDM 2010

\[ f_T = 644 \text{ GHz}, \ f_{\text{max}} = 681 \text{ GHz} @ 0.5 \text{ V} \]

Kim, EDL 2010

5-stage 480 GHz amp (G=11.7 dB)

Deal, MWCL 2010
InAlAs/ InGaAs HEMT mmw ICs

120-GHz-band link at Beijing Olympics
(10 Gb/s over 1 km)

RX, TX, PA single-chip modules:
0.1 μm InP HEMT

JC Fuji TV booth

Live-uncompressed HD video

TV station (Japan)

Water Cube

National Stadium

Courtesy of Akihiko Hirata (NTT)

Hirata, TMTT 2009
**InAlAs/ InGaAs Metamorphic HEMTs on GaAs**

- Comparable performance to InP substrate
- Improved manufacturability
- Lower cost
- Well established packaging technology

LNA NF vs. f

**Single-stage 500 GHz LNA (G=3.3 dB)**

LNA data courtesy of Phillip Smith (BAE Systems)
Polarization doping in Nitrides

AlGaN/GaN system uniqueness:
- Strong polarization “doping” \(\rightarrow\) high current operation
- High breakdown voltage \(\rightarrow\) high voltage operation
- High saturation velocity \(\rightarrow\) high frequency operation

Breakthrough high-f PAs

Courtesy of Debdeep Jena (U. Notre Dame)
Breakthrough RF Power in GaN HEMTs

Micovic, MTT-S 2010

94-95 GHz MMIC PAs:

Micovic, Cornell Conf 2010

\( P_{\text{out}} > 40 \text{ W/mm}, \) over 10X GaAs!

Wu, DRC 2006
GaN HEMT in the field

Counter-IED Systems (CREW)

200 W GaN HEMT for cellular base station
Kawano, APMC 2005

100 mm GaN-on-SiC volume manufacturing
Palmour, MTT-S 2010
Modulation-doped structures in physics
Cryogenic HEMTs in radioastronomy

- 1977: launch of Voyager 1 & 2, in mission to four planets
- 1987: AlGaAs/GaAs HEMT amplifiers delivered by GE to Very Large Array (Socorro, NM)
- 1989: Voyager 2 Neptune encounter
Modulation-doped structures in physics

AlGaAs/GaAs heterostructure: perhaps the most perfect crystalline interfacial system ever fabricated

\[ \mu = 3.6 \times 10^7 \text{ cm}^2/\text{V.s at 0.36 K} \]
\[ (n_s = 3 \times 10^{11} \text{ cm}^{-2}) \]

Umansky, JCG 2009

\[ \mu \uparrow: \text{less disorder} \quad \rightarrow \quad \text{new physics!} \]

Courtesy of Loren Pfeiffer (Princeton)
Fractional quantum-Hall effect

\[ \rho_{xy} = \frac{h}{ie^2} \]

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The Nobel Prize in Physics 1998

Robert B. Laughlin
Horst L. Störmer
Daniel C. Tsui

“For their discovery of a new form of quantum fluid with fractionally charged excitations”.

Discovered in sample with \( \mu_e = 9 \times 10^4 \text{ cm}^2/\text{V.s} \)

Tsui, PRL 1982
New international standard for Ohm: 
AlGaAs/ GaAs quantum-Hall bar array

Hall plateaus in Integral QHE determined by fundamental constants → use Hall resistance to define Ohm

AlGaAs/GaAs quantum-Hall bar array:
• adopted in 1990 as standard for Ohm
• precision: few parts in $10^9$
• 100 Hall bars
• $\mu_e \sim 6 \times 10^5$ cm$^2$/V.s

$\rho_{xy} = \frac{h}{ie^2}$

Previous Ohm standard (manganin wire):

Courtesy of Wilfrid Poirier (Laboratoire National de Métrologie et d’Essais)
Future prospects
New sensors

AlGaAs/GaAs 3-axis Hall sensors
Todaro JMM 2010

InAlSb/InAsSb Micro-Hall sensors
Bando, JAP 2009

AlGaAs/GaAs THz devices
Kawano, Phys E 2010

AlGaN/GaN Bio sensors
Niebelschutz, PSSc 2008
GaN power electronics

- GaN enables size shrink: $\sim 10^{-3}x$
- Si-like economics: $2-3x$ performance/cost advantage over Si

Briere, APEC 2011

$26B$ market in 2008
III-V CMOS

III-V FETs exceed logic performance of Si at 0.5 V

$\nu_{inj}$ in InGaAs $>2x$ higher than Si at half the voltage

$110B$ market in 2010!

del Alamo, IPRM 2011

Kim, IEDM 2009

$110B$ market in 2010!
Epilogue:

Kroemer’s Lemma of New Technology

“The principal applications of any sufficiently new and innovative technology have always been – and will continue to be – applications created by that technology.”

Kroemer, Rev Mod Phys 2000
Acknowledgements

- Ray Ashoori (MIT)
- Brian Bennett (NRL)
- Bobby Brar (Teledyne)
- P. C. Chao (BAE Systems)
- Takatomo Enoki (NTT)
- Augusto Gutierrez-Aitken (Northrop Grumman)
- Eric Higham (Strategy Analytics)
- Debdeep Jena (U. Notre Dame)
- Jose Jimenez (TriQuint Semiconductor)
- Marc Kastner (MIT)
- James Komiak (BAE Systems)
- Richard Lai (Northrop Grumman)
- Angie Locknar (MIT Libraries)
- Takashi Mimura (Fujitsu)
- Tomas Palacios (MIT)
- Loren Pfeiffer (Princeton)
- Philip Smith (BAE Systems)
- Tetsuya Suemitsu (Tohoku University)
- Ling Xia (MIT)