TRANSISTOR PRINCIPLES: FETs & PETs

Field Effect: Screening

Potential Effect: Control of a cathode work function
FETs:

\[ I = \frac{Q \cdot v}{L} \]

"Biblical" principle:

Q for Q
I for I

"Transit time" limitation:

\[ \tau > \frac{Q_{in}}{I_{out}} = \frac{L}{v} \]
Speed increases with current until exponential law fails at high currents

\[ I \sim e^{-\Phi/kT} \]

\[ \delta\Phi \sim \delta Q_{in} \]

\[ \tau \sim I^{-1} \]

PETs

PET $\rightarrow$ FET (space-charge effect)

\[ \tau \] limited by transit time across
Lect 11
Real Space Transfer Transistors

Charge Injection Transistor (CHINT)

Operating principle: Control of cathode temperature

\[ T_3 \]
\[ T_2 \]
\[ T_1 \]

\[ I_A \]

\[ V_A \]

Hot-electron cathode

Heating Voltage

Emmitter
Barrier
Collector
**Ballistic Electrons & Hot Electrons**

![Graph showing distribution of energy](image)

- \( f(E) \sim e^{-\frac{E}{kT_e}} \)
- \( f(E) \sim \delta(E-E_0) \)

**Ballistic Transistors**

- MOMOM (THETA)
- SMS
- HBT
- IBT
Real Space Transfer

Ballistic Electrons & Hot Electrons

\[ f(E) \sim e^{-E/kT_e} \]
\[ f(E) \sim \delta(E-E_0) \]
1984:

n AlGaAs
GaAs
AlGaAs
n GaAs

1990:

300 Å InGaAs n⁺
500 Å InGaAs n⁻
2000 Å InAlAs u
~ 1 μm InGaAs n⁺
InGaAs/InAlAs CHINT

P. Mensz, P. Garbinski, A. Cho, D. Sivco, S. Luryi

InGaAs/InAlAs CHINT

SD
C

Semi-insulating InP substrate

a: 5000 Å InGaAs n⁺ (Si:10¹⁹)
b: 500 Å InGaAs n⁻ (Si:10¹⁷)
c: 2000 Å InAlAs u
d: 500 Å InGaAs n (Si:10¹⁶)
e: 25 Å InAlAs n⁺ (Si:10¹⁹)
f: 200 Å InGaAs n⁺ (Sn:20²⁰)
g: 500 Å Ti/1000 Å Au
h: Si₃N₄

T = 300 K
W = 25 μm

Drain Current (mA)

Collector Current (mA)

Heating Voltage V_D

10
8
6
4
2
0 1 2 3 4 5
0 2 4 6 8 10

1 μm
Hot-Electron Instabilities in CHINT
Broken Symmetry States in CHINT

S. Luryi and M. Pinto

Multiply-connected $I-V$ characteristics

Anomalous collector-controlled states at $V_{DS} = 0$
Broken Symmetry States in CHINT

Anomalous collector-controlled states at $V_{DS} = 0$
Evolution of non-stationary states
Realization of anomalous states by rapid ramping of $V_C$

Critical ramping speed is determined by the rate at which the increasing fringing field ($\sim \frac{dV_C}{dt}$) is screened by channel electrons ($\sim v_{\text{sat}}$)
Formation of Hot-Electron Domains

![Graph showing formation of hot-electron domains.](image-url)
Lect 11
Real Space Transfer Transistors

Microwave Studies of CHINT

P. Menz, H. Schumacher, P. Garbinski, A. Cho, D. Skopp, S. Luryi
IEDM Tech. Dig. p. 395 (1990)
Microwave Performance of top-collector CHINT


![Graph showing current gain vs. frequency for different materials.](image-url)
Speed Limits of CHINT

Limiting mechanisms:

a. Establishment of hot-electron ensemble
   Phonons: ~ 1 ps  
ed-e interaction < 1 ps  
   (if concentration not too low)

b. Charging time
   transit over high-field regions
   ~ 2-3 ps  
   $f_T \sim 80 - 50 \text{ GHz}$

c. Parasitic $C-D$ capacitance
   presently dominates

Collector-top
CHINT preferable

"FET like" but not limited by time of flight $S \rightarrow D$
in small-signal operation

K. Maezawa and T. Mizutani,

CHINT vs FET
Hot electron ensemble equilibrates via e-e interaction

RST is due to electrons in high-energy tails of the distribution function

Tails are repopulated "instantaneously" from the main part of distr. (at high enough conc.)

The effective temperature of electrons is determined by energy balance

\[ T_e = f(\mid V_{SD}\mid) \]

\( T_e \) can be very high, more than 1000 K

The fundamental symmetry of charge injection by RST

Can interchange

S \( \xrightarrow{\text{DS}} \) D

Collector current will not change!
CHINT logic

S. Luryi, P. Mensz, M. Pinto, P. Garbinski, A. Cho, D. Sivco

<table>
<thead>
<tr>
<th>S</th>
<th>D</th>
<th>I_C</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>low</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>high</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>high</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>low</td>
<td>1</td>
</tr>
</tbody>
</table>

XNOR (S, D)

L = XOR (S, D)
Light-Emitting CHINT

S. Luryi, Appl. Phys. Lett. 58, 1727 (1990)

RST of electrons into a complementary collector

Equilibrium

Flat bands

Operating regime

$V_{FB}$

$V_C$

$E_C$

$E_V$

$E_F$
Transistors

L = XOR (S, D)

Light-emitting logic RST device

Mastrapasqua et al
IEEE TED-40, 250 (1993)
Light = \text{xor}(S, D)

\begin{align*}
V_{C} &= 3 \text{ V} \\
V_D (\text{V}) &= \begin{cases} 
1.5 & \text{if } 0-0 \\
0 & \text{otherwise}
\end{cases} \\
V_S (\text{V}) &= \begin{cases} 
1.5 & \text{if } 1-0 \\
0 & \text{elsewhere}
\end{cases} \\
\text{Out} : 1 & 0 & 1 & 0
\end{align*}

\begin{align*}
\text{Light Output} \quad P_L (\mu \text{W}) &= \begin{cases} 
1.45 & \text{if } 0-1 \\
0.43 & \text{if } 1-1 \\
0.36 & \text{if } 1-0 \\
< 10^{-4} & \text{if } 0-0
\end{cases} \\
T &= 290 \text{ K} \\
T &= 235 \text{ K} \\
T &= 100 \text{ K}
\end{align*}
\textbf{Current} = \texttt{xor}(S, D)

\[ V_C = 3 \text{ V} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}

- Time range: 0 to 2.5
- \( V_D \) (V) range: 0 to 1.5
- \( V_S \) (V) range: 0 to 1.5
- Collector Current \( I_C \) (mA) range: 0 to 2
- \( V_C = 3 \text{ V} \)

- Temperature:
  - \( T = 290 \text{ K} \): 1.87 mA
  - \( T = 235 \text{ K} \): 0.98 mA
  - \( T = 100 \text{ K} \): 0.52 mA

- Output:
  - \( 1 \): 0.06 mA
  - \( 0 \): 2x10^{-4} mA
  - \( 1 \): 5x10^{-8} mA
  - \( 0 \): 0.36 mA

\textit{Note:}
- \( V_c = 3 \text{ V} \)
Band alignment in InGaAs/InAlAs/InGaAs n-i-p heterostructure

\[ \Delta E_V = 0.2 \text{ eV} \]

\[ \Delta E_C = 0.5 \text{ eV} \]

Leakage: holes from collector
RST: electrons from emitter channel
Symmetry under interchange does not imply equivalence between + and - $V_D$

When $V_D < 0$ the D electrode acts as a source, gated by the collector voltage
Symmetry of the CHINT

\[
[ V_D, V_C ] \equiv [ -V_D, (V_C - V_D) ]
\]

Reflection plane

Collector current invariant under interchange

S \leftrightarrow D

A similar symmetry exists in FET:

\[
[ V_D, V_G ] \equiv [ -V_D, (V_G - V_D) ]
\]

but not so important, because

G is not the output terminal
OUT = NORAND \( (X_1, X_2, X_3) \)

\[
= (X_1 \land X_2 \land X_3) \lor (\overline{X_1} \land \overline{X_2} \land \overline{X_3})
\]
Light-Emitting Device with OR-NAND Logic Function

M. Mastrapasqua et al.,
IEDM-92, p. 659;

$L = \text{OR } (1, 2)$ if $3 = \text{low}$

$L = \text{NAND } (1, 2)$ if $3 = \text{high}$
OR-NAND Logic

input: "0" = 0  
voltages: "1" = 3 V  

T = 300 K  

V_C = 2.4 V

V_3

V_2

V_1

I_C (mA)

P_L (µW)

NAND  OR

0  1  20  40  0  1

33  35  33  40  36  34

17  18  18  16  16  18

0  0.066
Cancellation of symmetry break by off-center trench misalignment

<table>
<thead>
<tr>
<th>input $V_{1, V_2}$</th>
<th>0, 1</th>
<th>0, 0</th>
<th>1, 0</th>
<th>1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>or $V_3 = 0$</td>
<td>1 -&gt; 2</td>
<td></td>
<td>3 -&gt; 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 -&gt; 2</td>
<td></td>
<td>2 -&gt; 1</td>
<td></td>
</tr>
<tr>
<td>nand $V_3 = 1$</td>
<td>1 -&gt; 3</td>
<td>1 -&gt; 3</td>
<td>2 -&gt; 1</td>
<td>2 -&gt; 3</td>
</tr>
</tbody>
</table>

"working" channels
Characteristics of nearest pairs of electrodes

T = 300 K
V_C = 2.3 V
W = 40 \mu m
Leakage vs RST

vastly different radiative efficiency (InGaAs/InAlAs)

holes injected in the channel recombine non-radiatively

In contrast: InGaAs/InP devices exhibit similar electrical and optical behavior
Top collector complementary and unipolar devices

- Microwave studies: slow roll-off at high frequencies
- Electroluminescence spectra of hot electron-hole plasma in active layer
- Hot-carrier thermometer

Hot-electron instabilities

- Broken symmetry
- Collector-controlled states
- Formation of hot-electron domains
- Multiply-connected IV

Impact ionization studies

- RST of secondary holes from the channel

Noise studies

- Space-charge smoothing of shot noise?

... Lot of fun
Real-space transfer of secondary holes

"normally-on" channel

Holes, impact-ionized near the drain, accelerate toward the source and undergo RST.

Band diagram near the source.
Summary

Transistor Principles

PETs & FETs
Ballistic and Hot electrons
Real Space Transfer
CHINT

Charge Injection Logic

Symmetry of CHINT
Multi-terminal logic elements
NORAND

Light emitting RST devices

Complementary CHINT
InGaAs/InAlAs implementation
ORNAND

Future

More fun
Reprogrammable circuits
Self-organizing systems?
Logic lasers
Massively parallel systems