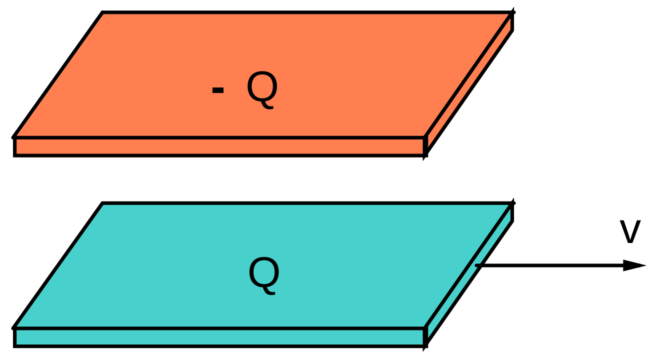
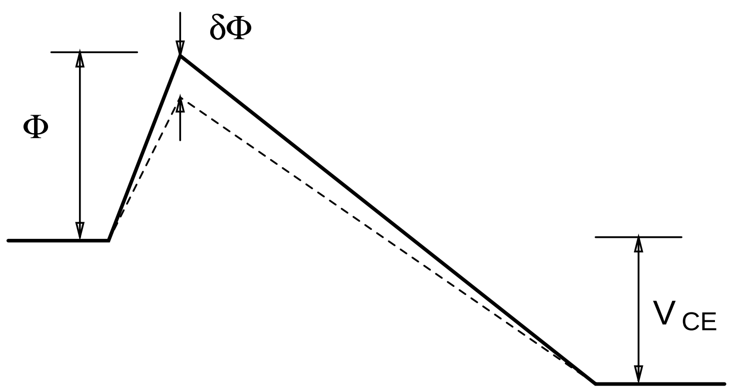
TRANSISTOR PRINCIPLES : FETs & PETs

Field Effect: Screening

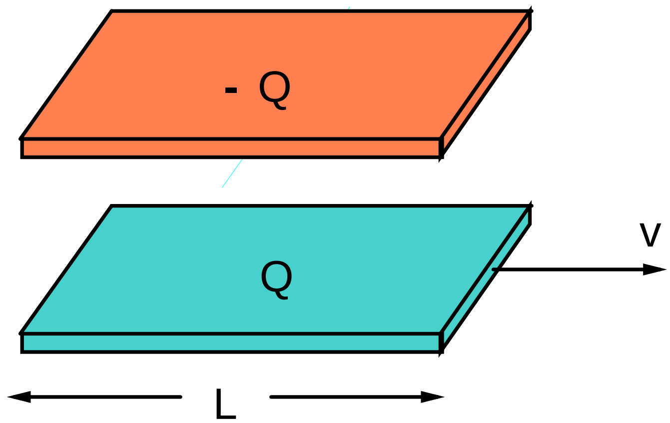


Potential Effect: Control of a cathode work function



FETs:

$$I = \frac{Q\,v}{L}$$



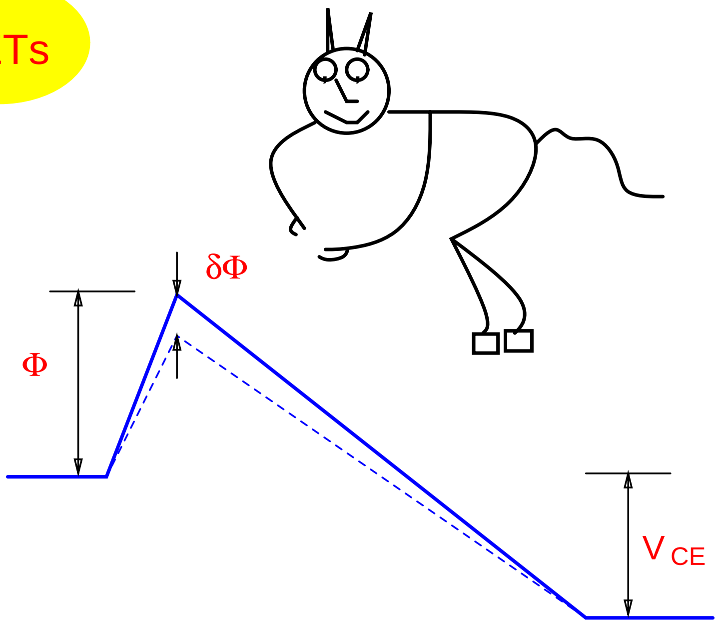
"Biblical" principle:

Q for Q
I for I

"Transit time" limitation :

$$\tau > \frac{Q_{in}}{I_{out}} = \frac{L}{v}$$

PETs



$$I \sim e^{-\Phi/kT}$$

$$\delta\Phi \sim \delta Q_{in} \longrightarrow \tau \sim I^{-1}$$

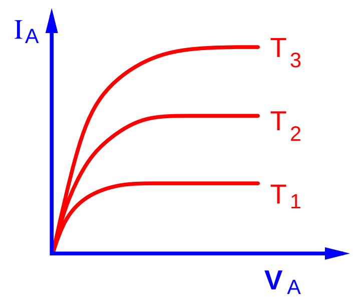
Speed increases with current until exponential law fails at high currents

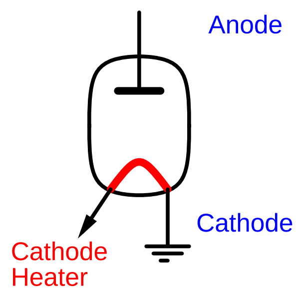
PET $\longrightarrow$ FET (space-charge effect)

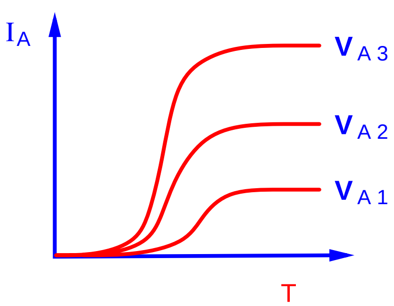
τ limited by transit time across

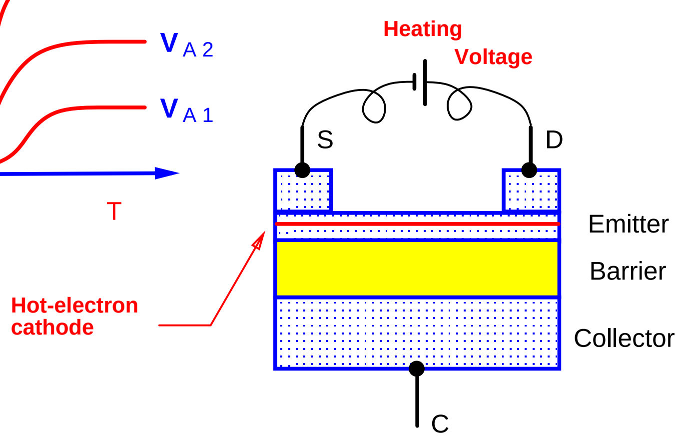
Charge Injection Transistor (CHINT)

Operating principle: **Control of cathode temperature**

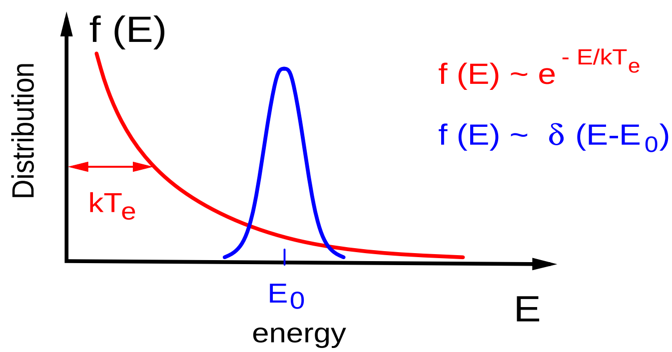


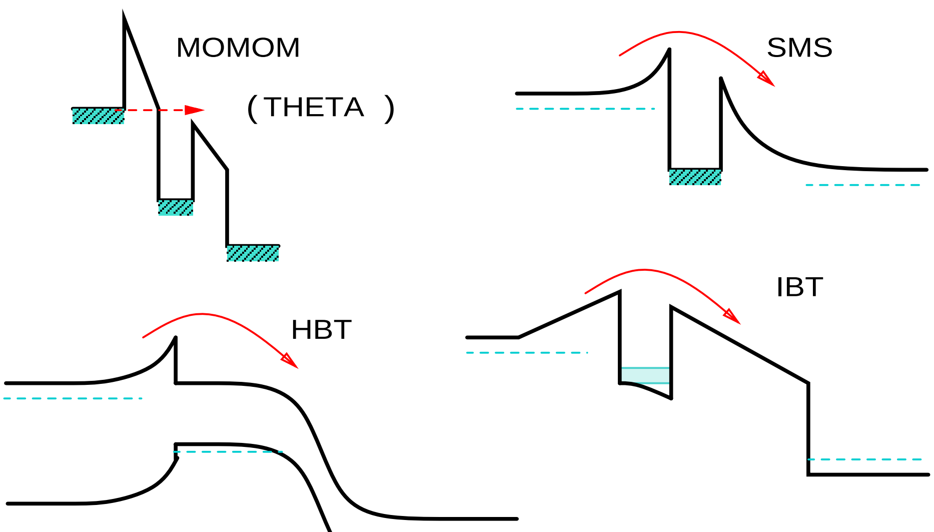






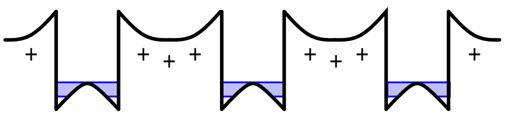
Ballistic Electrons & Hot Electrons

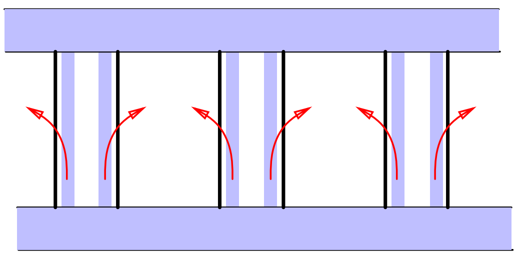


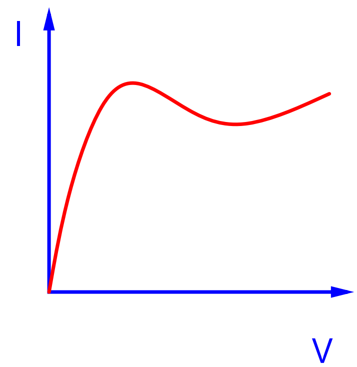


Ballistic Transistors

Real Space Transfer





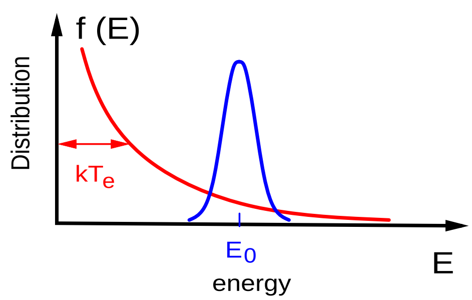


Ballistic Electrons

& Hot Electrons

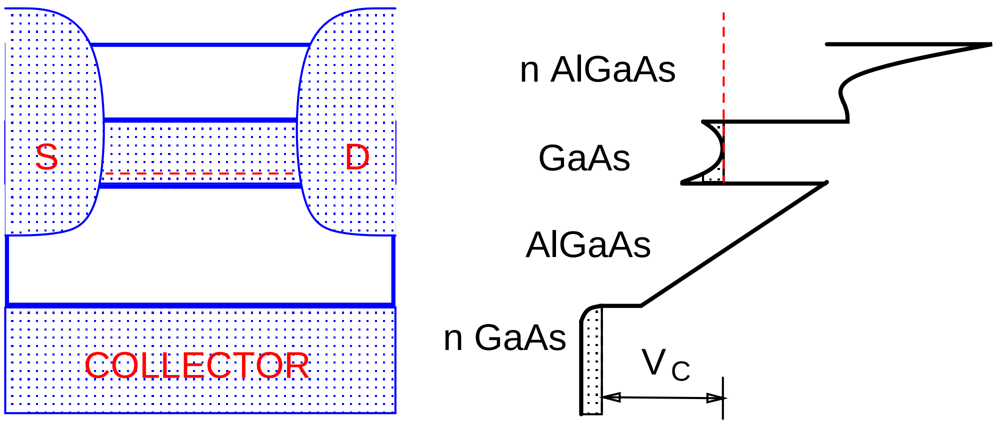
$f(E) \sim e^{-E/kT_e}$

$f(E) \sim \delta(E-E_0)$

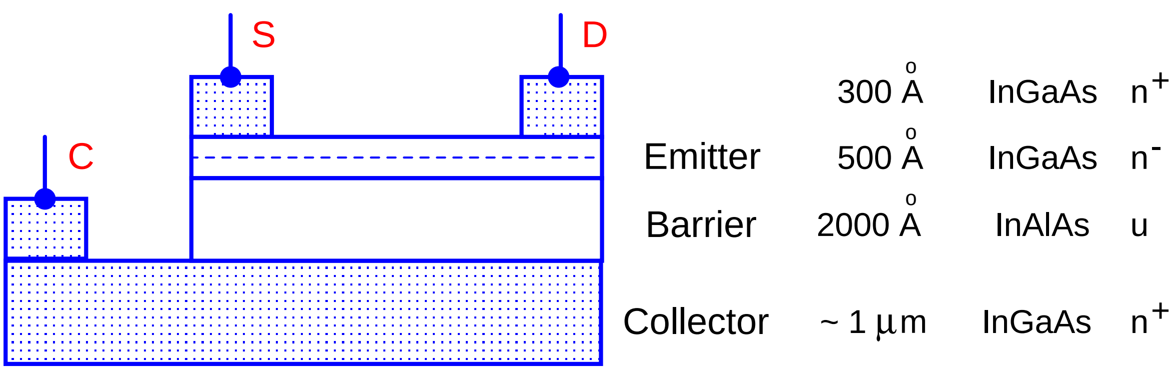


CHINT Structures

1984:

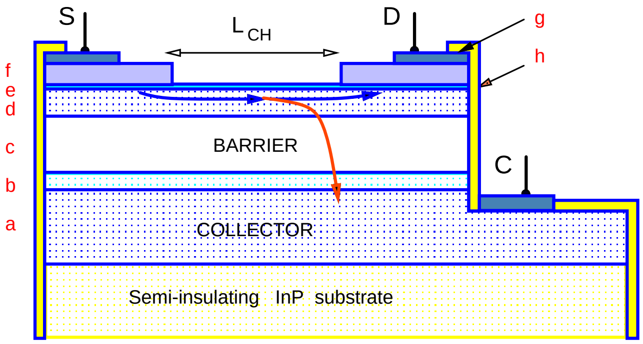


1990:

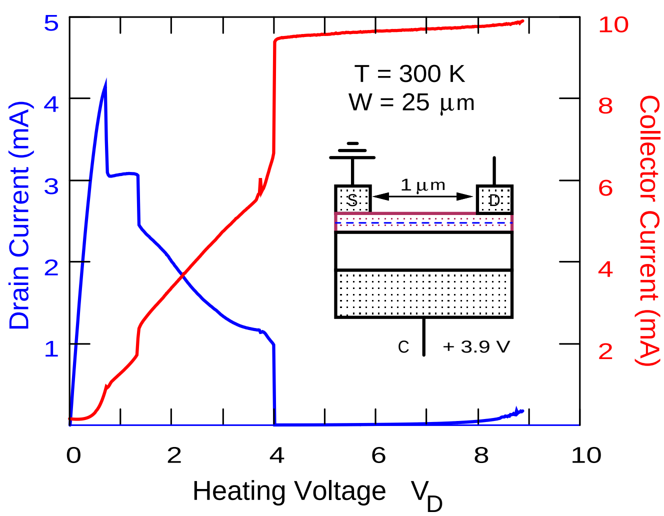


InGaAs/InAlAs CHINT

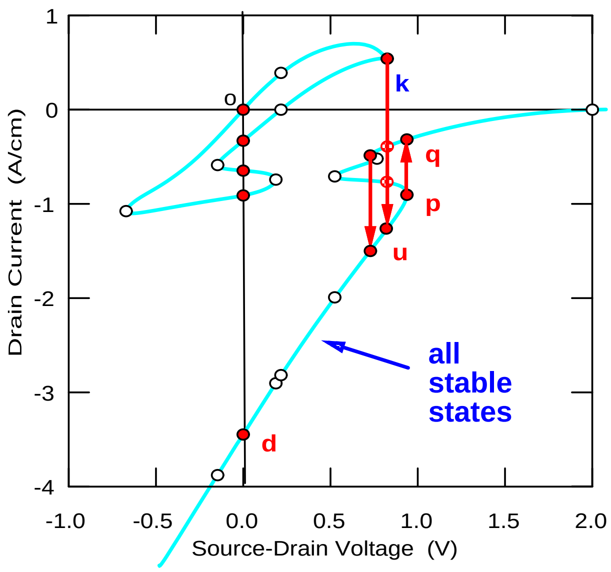
P.Mensz, P.Garbinski, A.Cho, D.Sivco, S.Luryi
Appl. Phys. Lett. **57**, 2563 (1990)

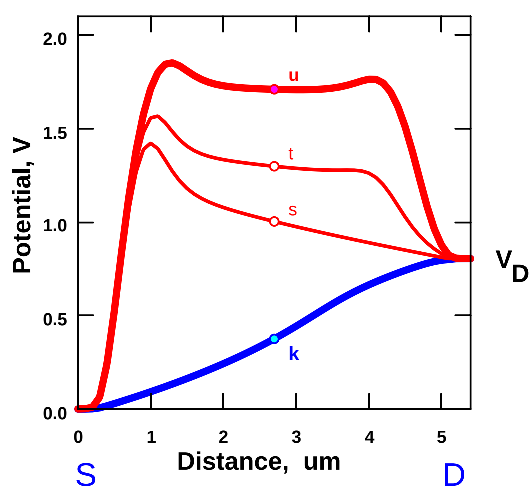


a: 5000 Å InGaAs n^+ (Si:10^{19})
b: 500 Å InGaAs n^- (Si:10^{17})
c: 2000 Å InAlAs u
d 500 Å InGaAs n (Si:10^{16})
e: 25 Å InAlAs n^+ (Si:10^{19})
f: 200 Å InGaAs n^+ (Sn:10^{20})
g: 500 Å Ti / 1000 Å Au
h: Si_3N_4



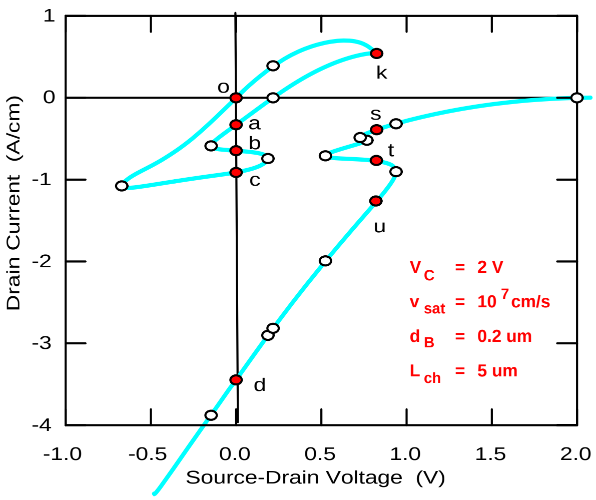
Hot-Electron Instabilities in CHINT





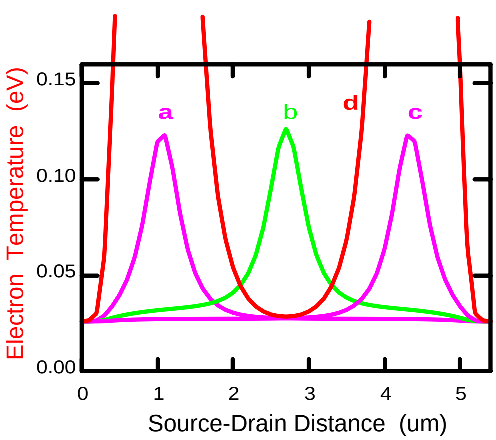
Broken Symmetry States in CHINT

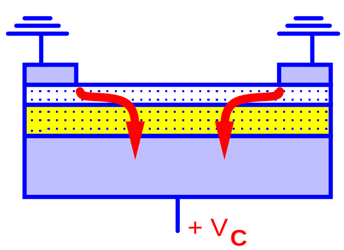
S. Luryi and M. Pinto
Phys. Rev. Lett. **67**, 2351 (1991)



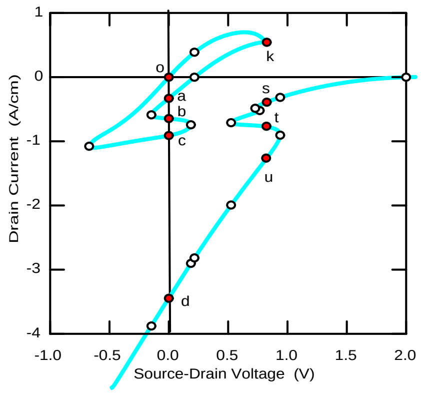
Multiply-connected
I - V characteristics

Anomalous
collector-controlled
states at $V_{DS} = 0$

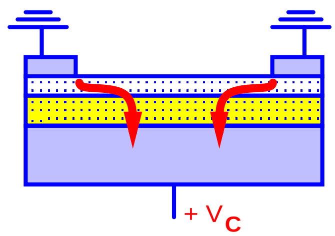


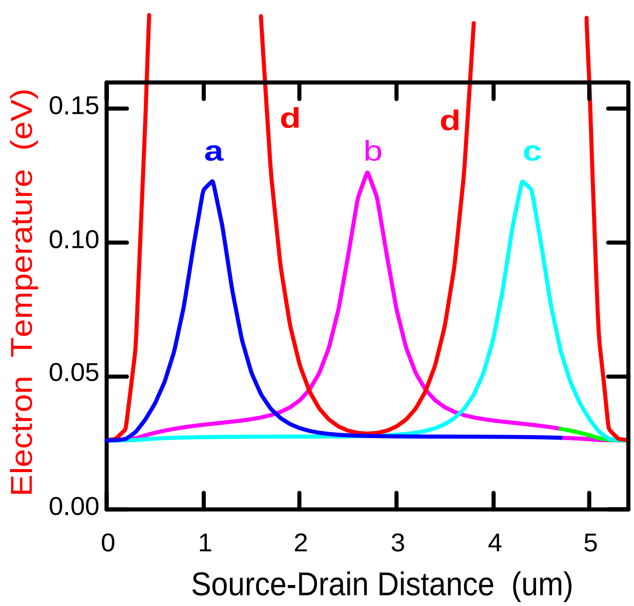


Broken Symmetry States in CHINT

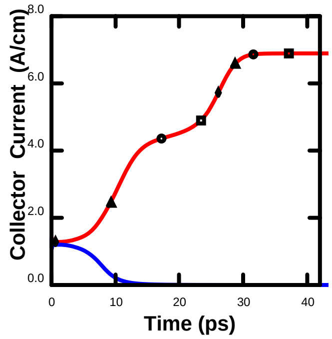


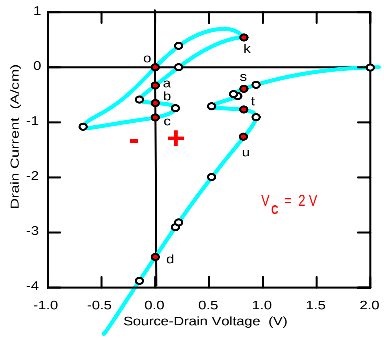
Anomalous collector-controlled states at $V_{DS} = 0$

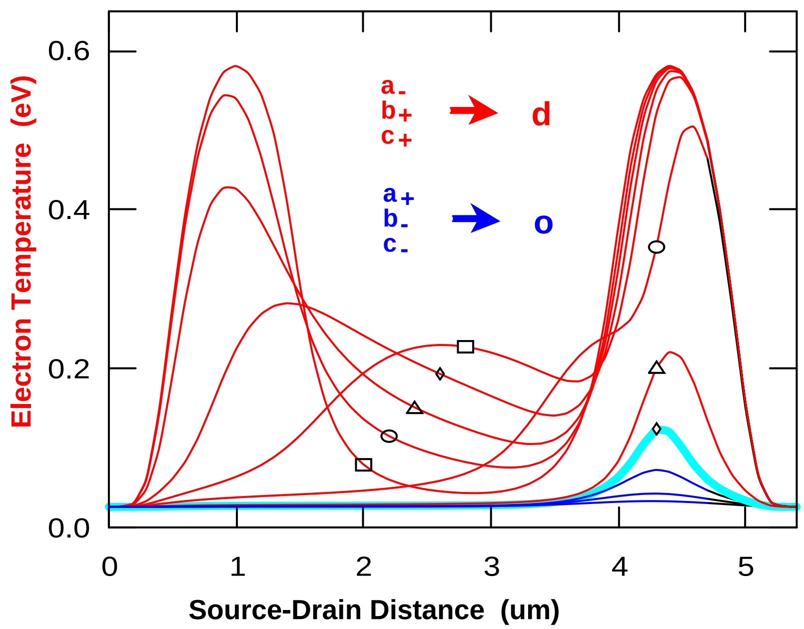




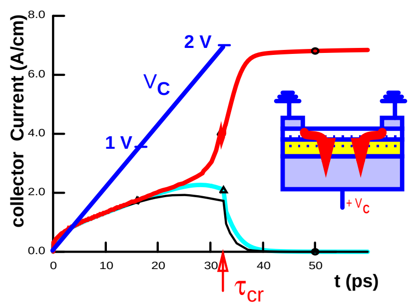
Evolution of non-stationary states

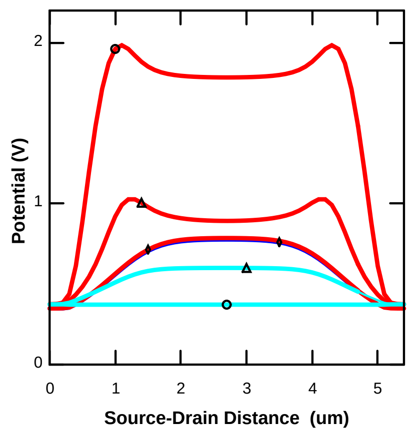




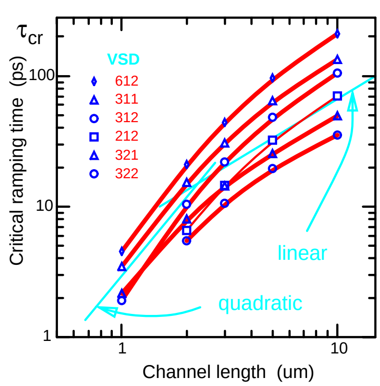


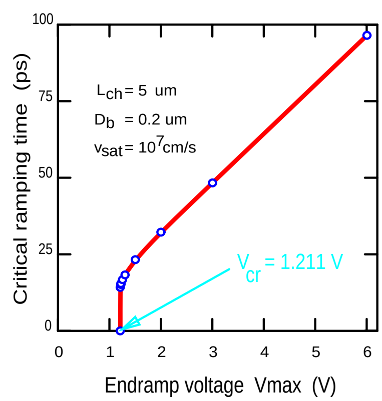
Realization of anomalous states by rapid ramping of V_C



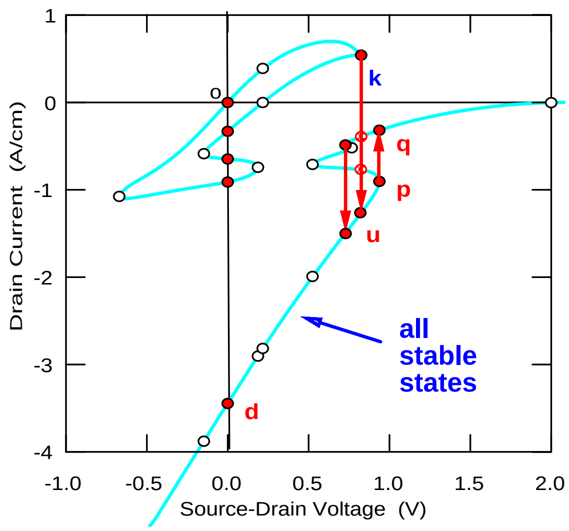


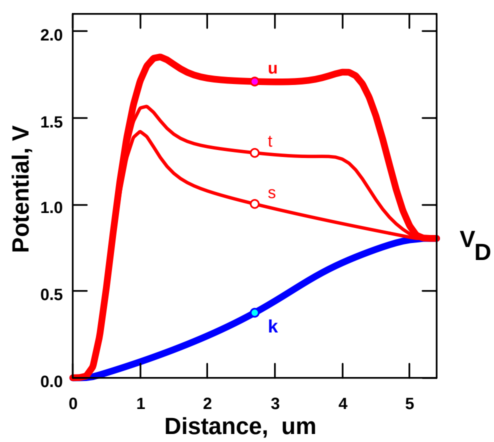
Critical ramping speed is determined by the rate at which the increasing fringing field **(~ dV_C /dt)** is screened by channel electrons **(~ v_{sat})**





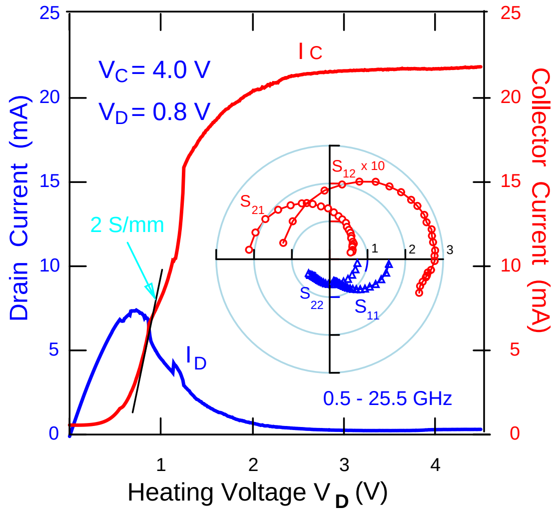
Formation of Hot-Electron Domains

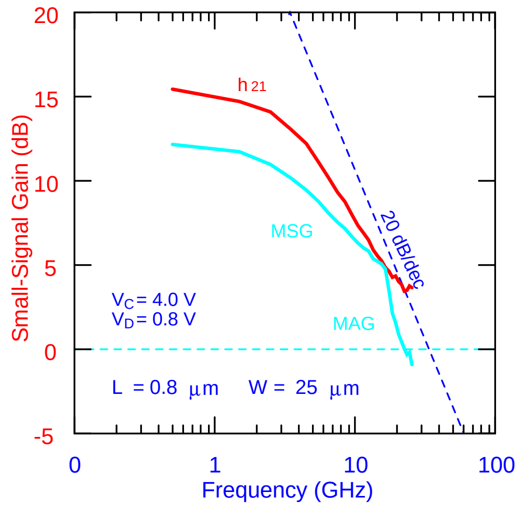




Microwave Studies of CHINT

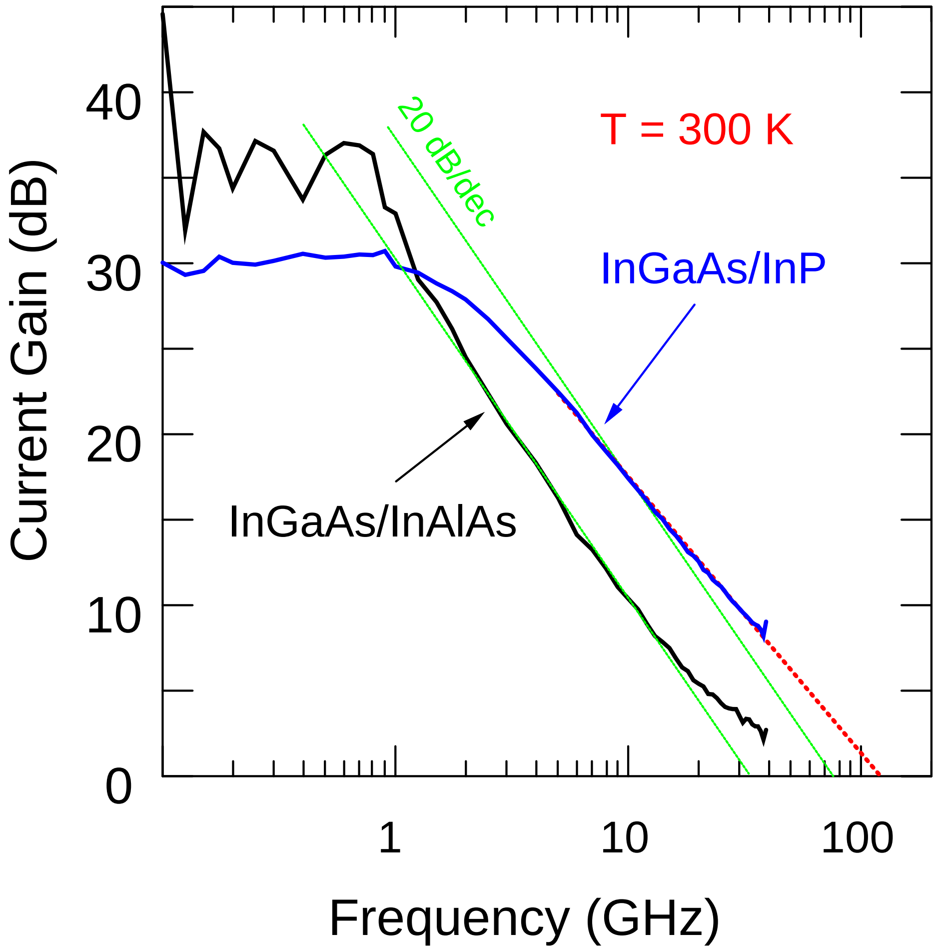
P.Mensz, H.Schumacher, P.Garbinski, A.Cho, D.Sivco, S.Luryi
IEDM Tech. Digest, p. 395 (1990)



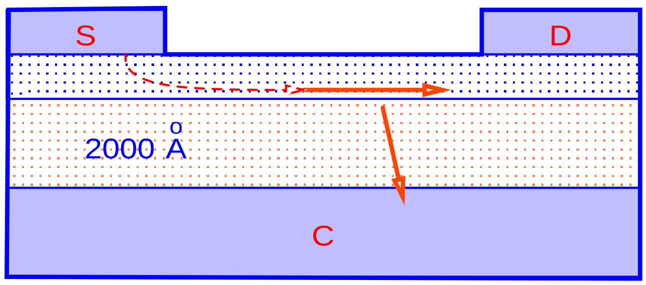


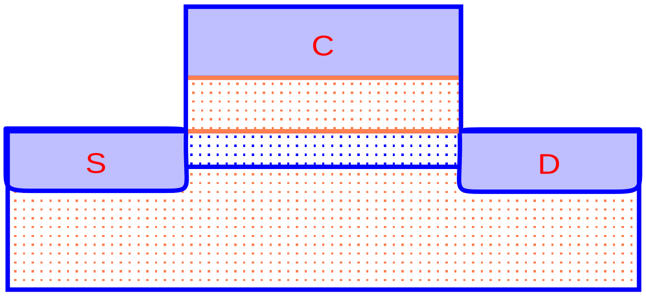
Microwave Performance of top-collector CHINT

G. Belenky, P. Garbinski, P. Smith, S. Luryi
A. Y. Cho, R. A. Hamm, D. L. Sivco (1993)



Speed Limits of CHINT





Limiting mechanisms:

a. Establishment of hot-electron ensemble

Phonons: ~ 1 ps
e-e interaction < 1ps
(if concentration not too low)

b. Charging time

transit over high-field regions

~ 2-3 ps f_T ~ 80 - 50 GHz

c. Parasitic **C-D** capacitance

presently dominates

Collector-top CHINT preferable

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

K. Maezawa and T. Mizutani, Jpn. J. Appl. Phys. 30, 1190 (1991)

CHINT vs FET

Physical Picture

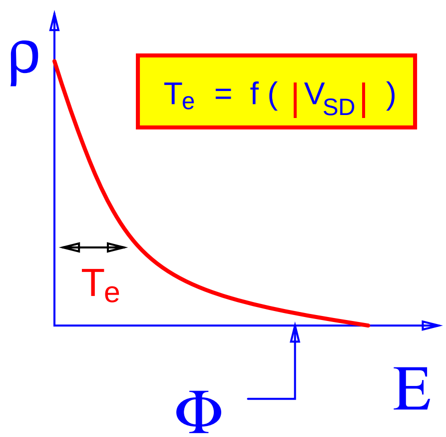
Hot electron ensemble
equilibrates via e-e interaction

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

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

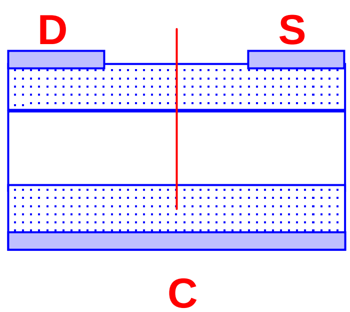
The effective temperature
of electrons is determined
by energy balance

T_e can be very high,
more than 1000 K



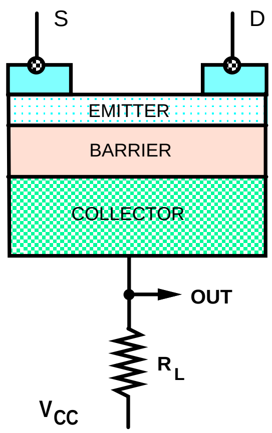
The fundamental symmetry
of charge injection by RST

Can interchange
S ⟷ D
collector current
will not change !



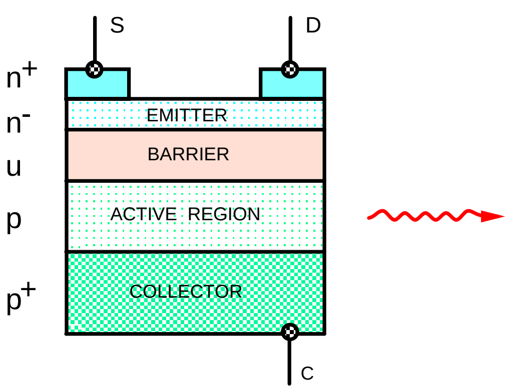
CHINT logic

S.Luryi, P.Mensz, M.Pinto, P.Garbinski, A.Cho, D.Sivco
Appl. Phys. Lett. **57** , 1787 (1990)



S	D	I_C	OUT
0	0	low	1
0	1	high	0
1	0	high	0
1	1	low	1

XNOR (S , D)

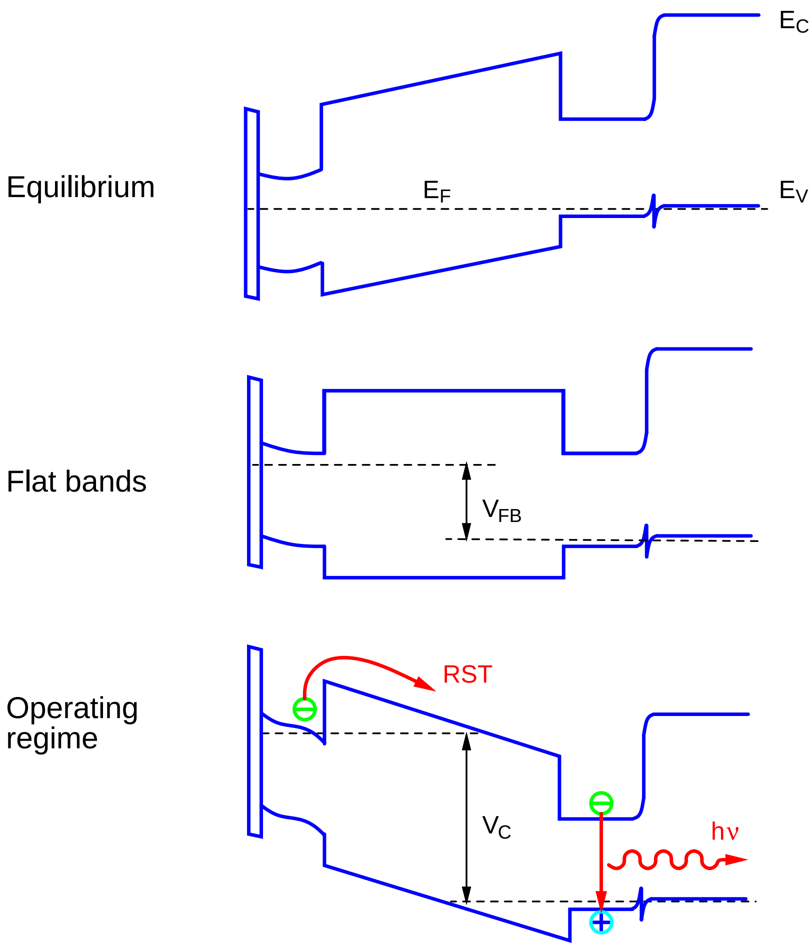


L = XOR (S , D)

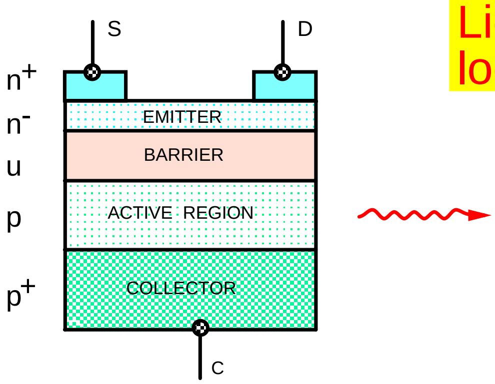
Light-Emitting CHINT

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

RST of electrons
into a complementary collector

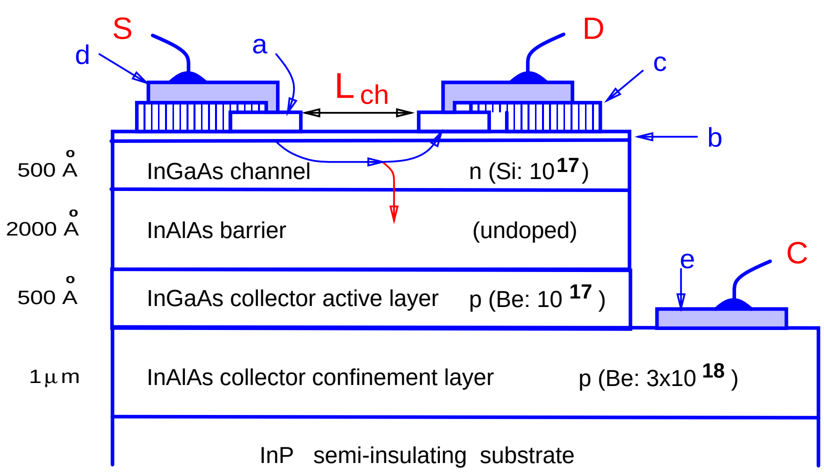


Light-emitting logic RST device



L = XOR (S , D)

Mastrapasqua et al
Appl. Phys. Lett. 60, 2415 (1992)
IEEE TED-40, 250 (1993)



a: 200 Å InGaAs, n (Sn: 10^{20})

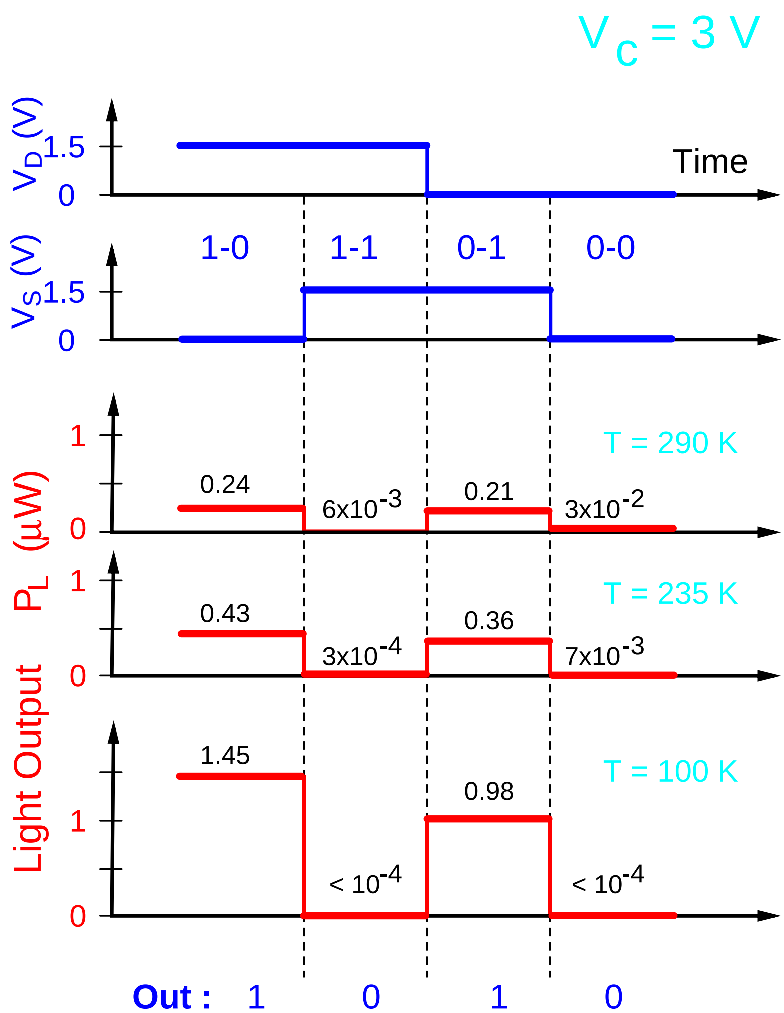
b: 25 Å InAlAs, n (Sn: 10^{19})

c: 2500 Å Si_3N_4

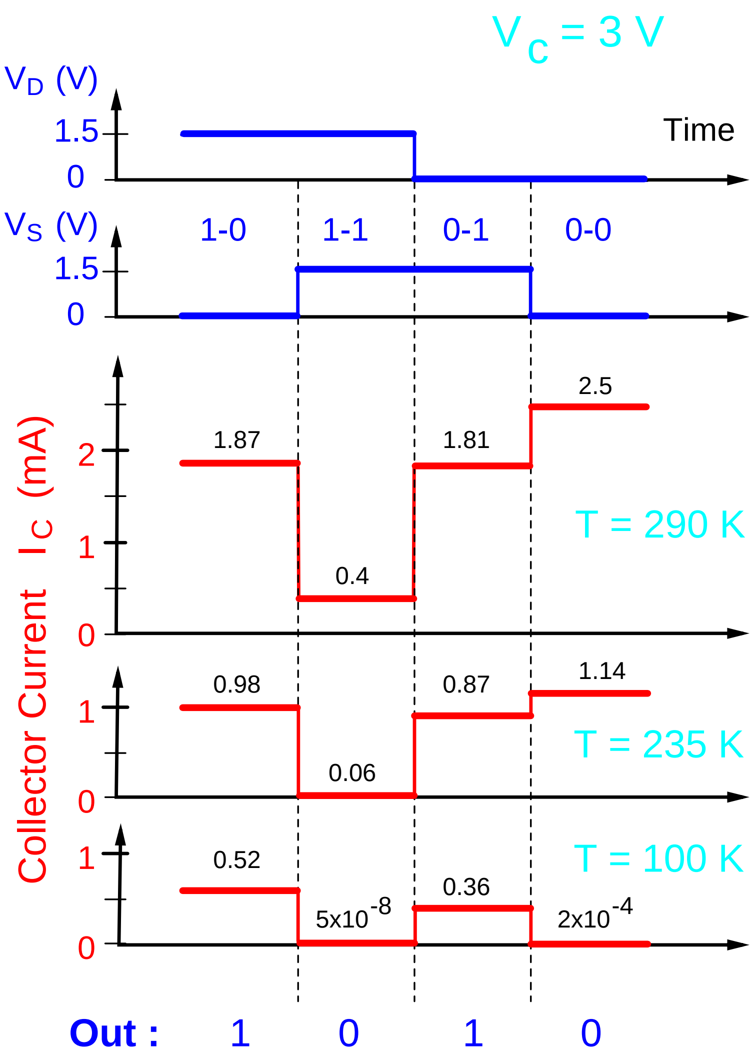
d: 300 Å Ti / 1800 Å Au

e: 800 Å AuBe / 2000 Å Au

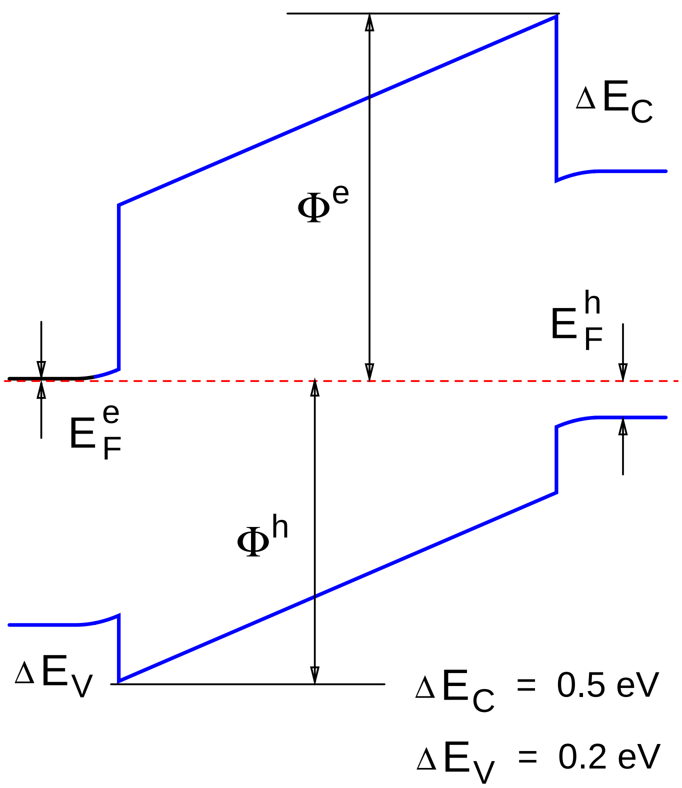
Light = xor (S , D)


$V_C = 3$ V
V_D (V)
1.5
0
Time
1-0
1-1
0-1
0-0
V_S (V)
1.5
0
P_L (µW)
Light Output
T = 290 K
1
0
0.24
$6x10^{-3}$
0.21
$3x10^{-2}$
T = 235 K
1
0
0.43
$3x10^{-4}$
0.36
$7x10^{-3}$
T = 100 K
1
0
1.45
$< 10^{-4}$
0.98
$< 10^{-4}$
Out : 1 0 1 0

Current = xor (S , D)

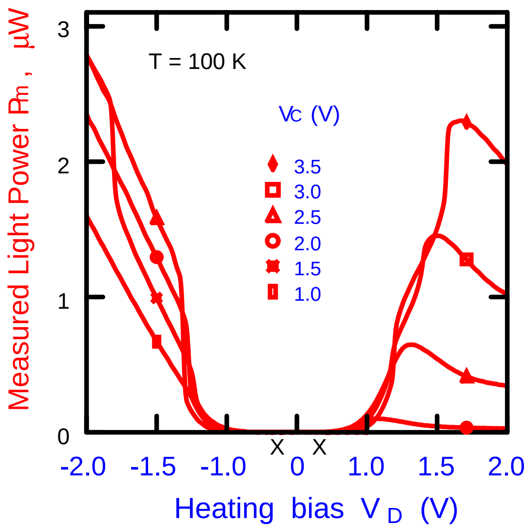


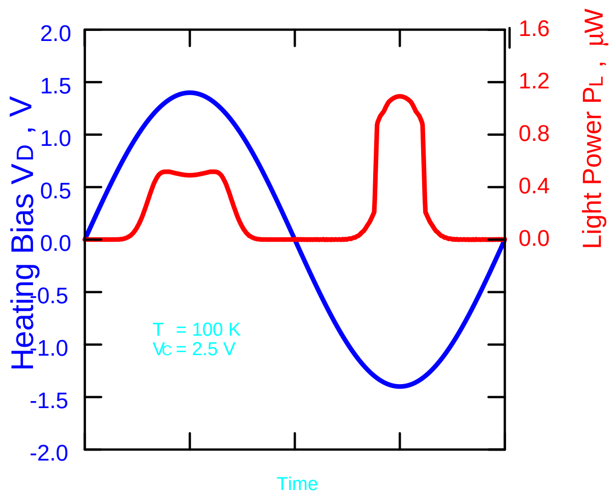
Band alignment in
InGaAs/InAlAs/InGaAs
n-i-p heterostructure

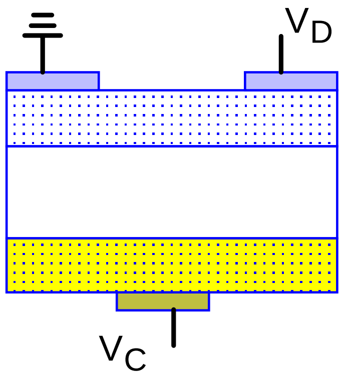


Leakage: holes from collector
RST: electrons from emitter channel

"Frequency Doubler"







Symmetry under interchange
does not imply equivalence
between + and - V_D

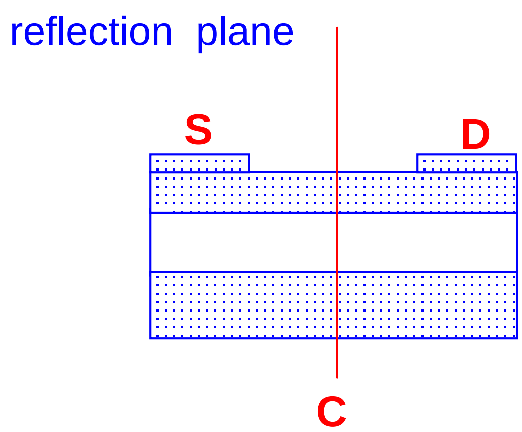
When $V_D < 0$
the D electrode acts as a source,
gated by the collector voltage

Symmetry of the CHINT

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

Collector current invariant under interchange

S ⟷ D



a similar symmetry exists in FET:

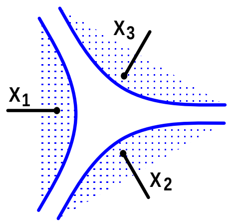
$$[\,V_D\,, V_G\,] \equiv [-V_D\,, (V_G - V_D)]$$

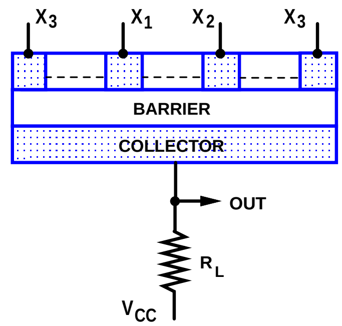
but not so important, because

G is not the output terminal

CHINT logic

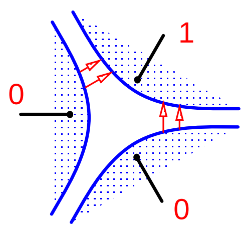
S. Luryi and M. Pinto
US Patent **4,999,687**

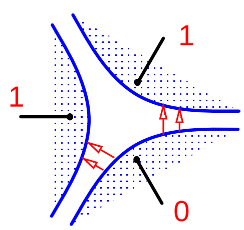




$$\text{OUT} = \text{NORAND}\ (X_1, X_2, X_3)$$

$$= (X_1 \cap X_2 \cap X_3) \cup (\overline{X}_1 \cap \overline{X}_2 \cap \overline{X}_3)$$





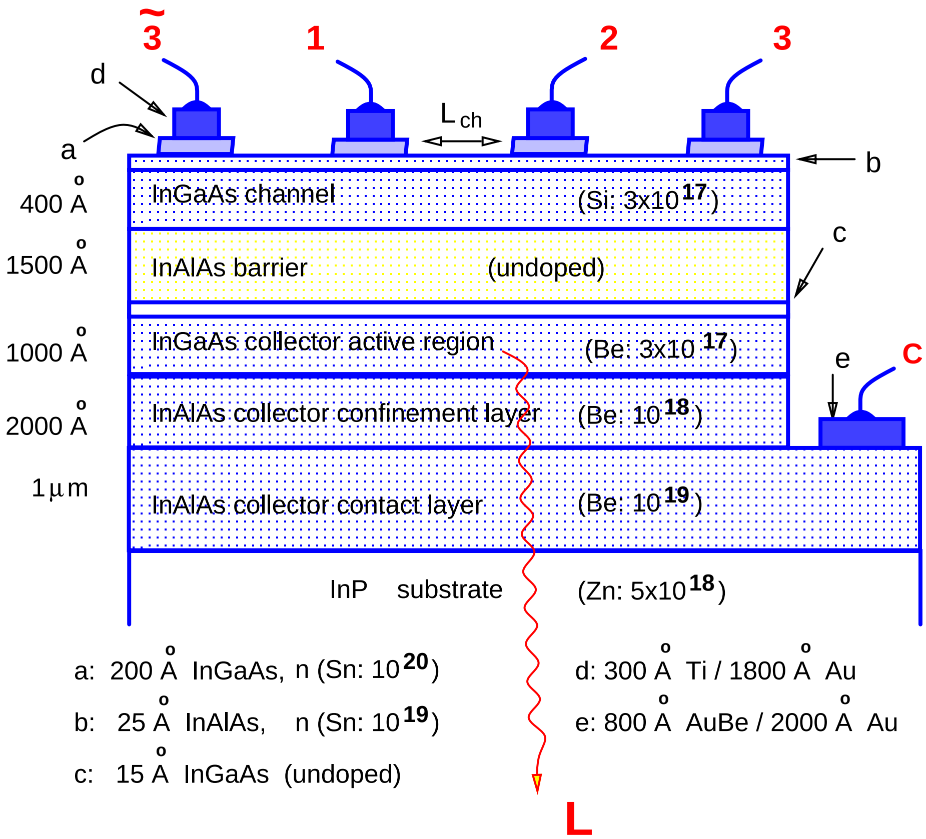
X_1	X_2	X_3	OUT	
0	0	0	1	NOR
1	0	0	0	
0	1	0	0	
1	1	0	0	
0	0	1	0	AND
1	0	1	0	
0	1	1	0	
1	1	1	1	

Light-Emitting Device with OR-NAND Logic Function

M. Mastrapasqua et al., IEDM-92, p. 659; IEEE TED-40 (Aug, 1993)

L = OR (1 , 2) if 3 = low

L = NAND (1 , 2) if 3 = high

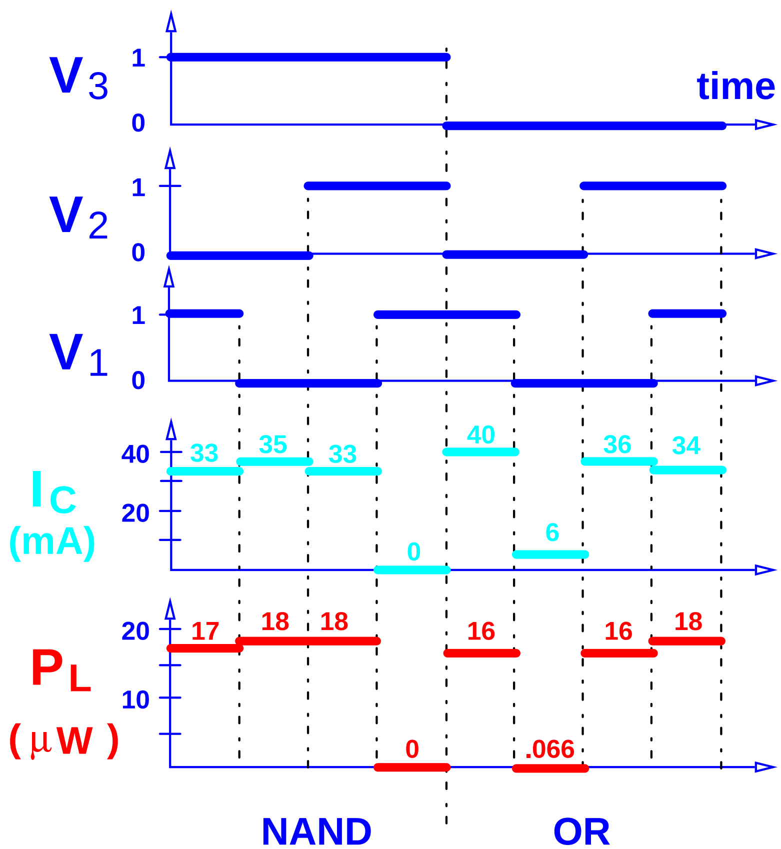


OR-NAND Logic

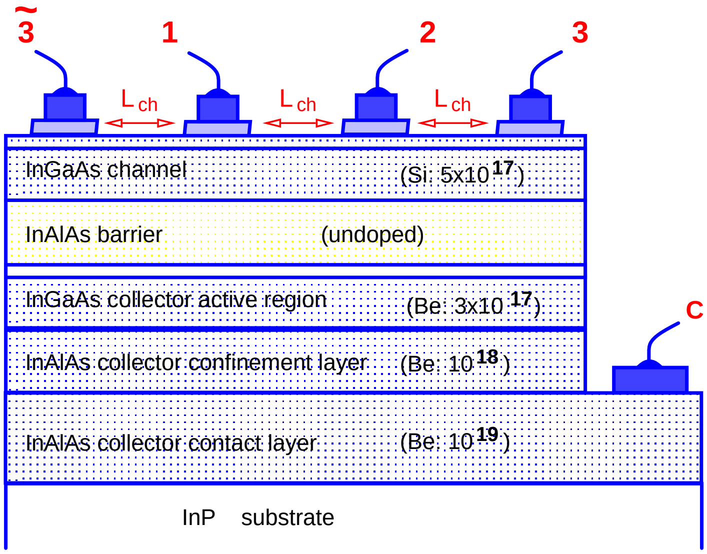
input voltages: "0" = 0, "1" = 3 V

T = 300 K

V_c = 2.4 V



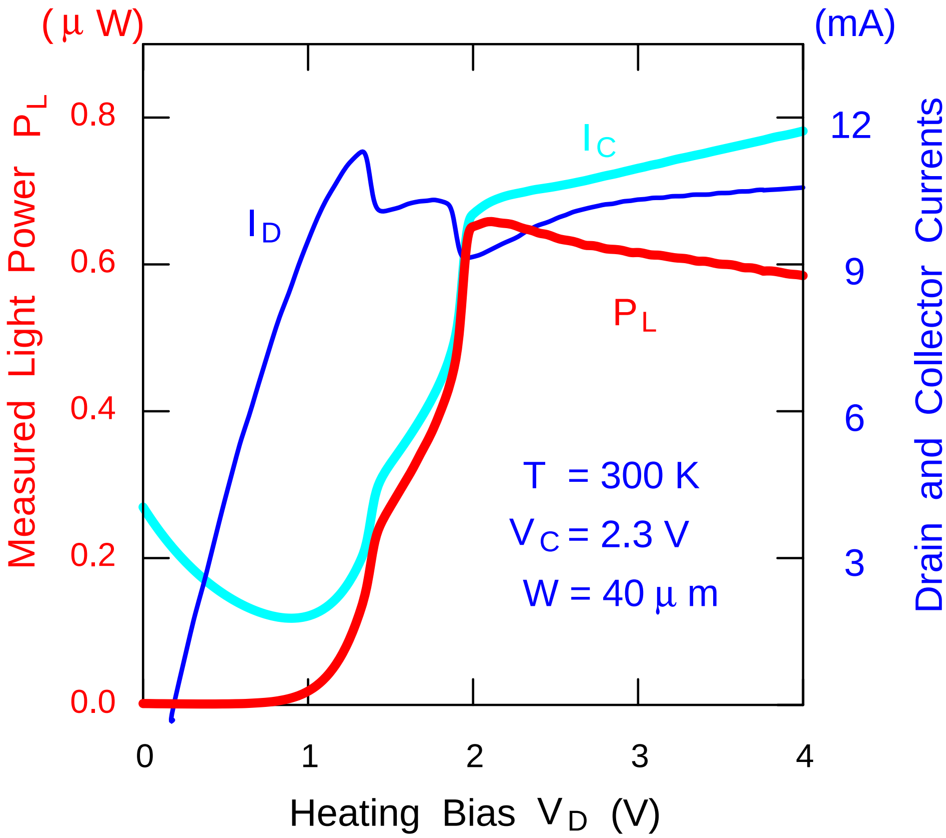
Cancellation of symmetry break by off-center trench misalignment



input V_1, V_2	0, 1	0, 0	1, 0	1, 1
or $V_3 = 0$	1 → 2 3 → 2		$\tilde{3}$ → 1 2 → 1	$\tilde{3}$ → 1 3 → 2
nand $V_3 = 1$	1 → $\tilde{3}$ 1 → 2	1 → $\tilde{3}$ 2 → 3	2 → 1 2 → 3	

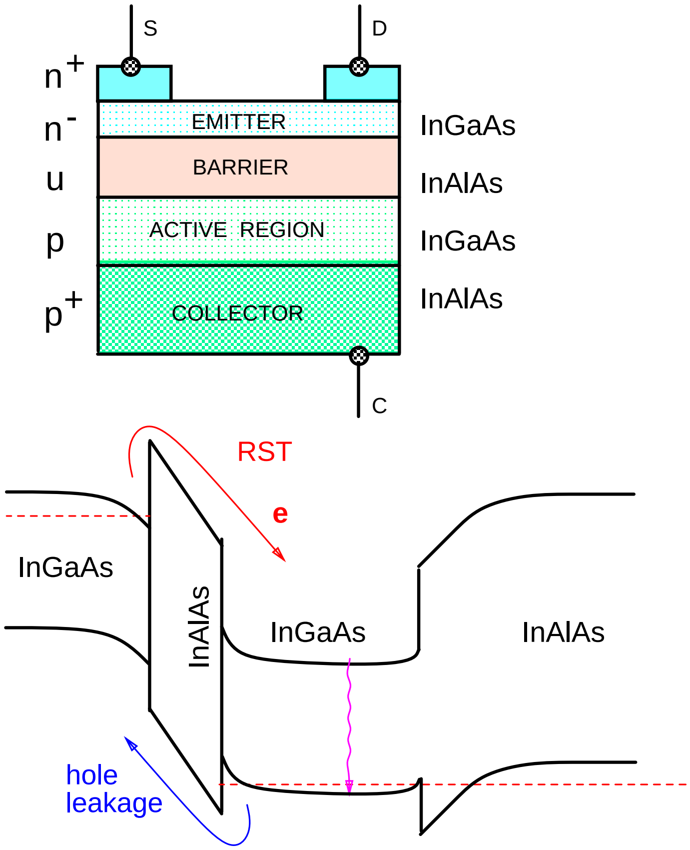
"working" channels

Characteristics of nearest pairs of electrodes



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

Physics with CHINT

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

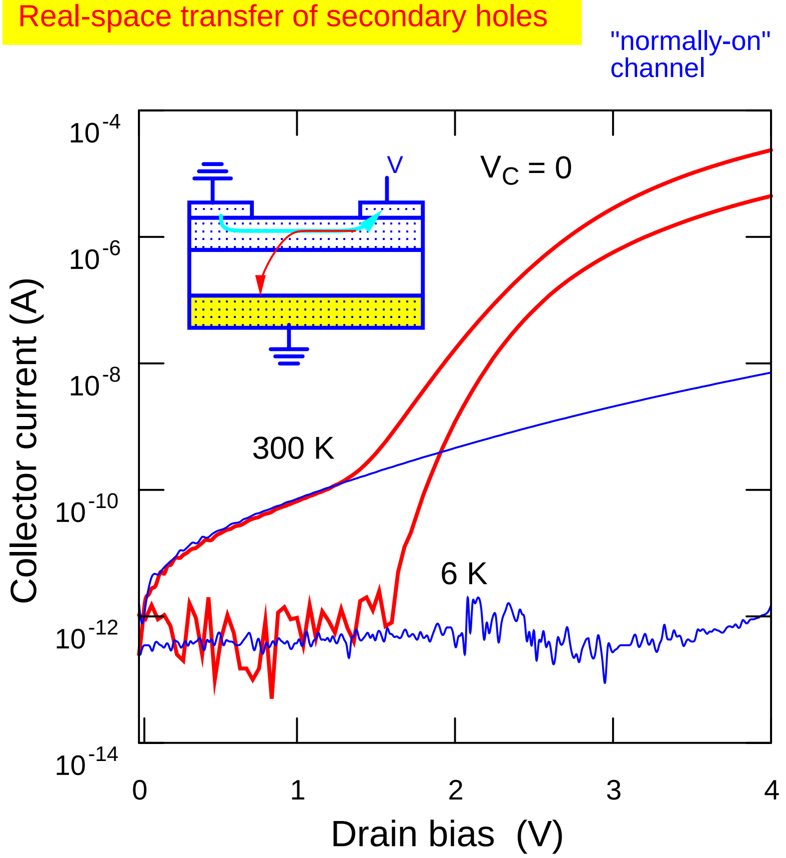
Noise studies

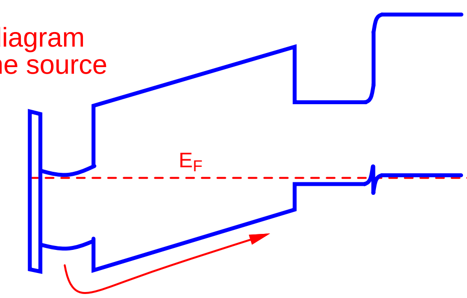
Space-charge smoothing of shot noise ?

...

Lot of fun

Real-space transfer of secondary holes





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

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