What’s a YBS?

Outline

- Why the YBS?
- Characteristics of the heterostructure
- Device fabrication
- How it works
- Problems
- Applictions

Need for efficient electronic switches

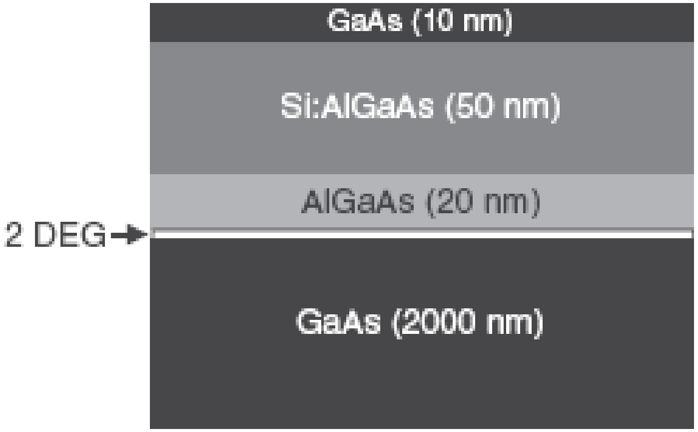
Need:

- High electronic speed
- Low power dissipation
- Large range of the potential applied values to reduce the switch error

YBS can be a solution?

Charatteristics of the heterostructure (1)

- A heterostructure (or heterojunction) is a *p-n* junction realized between two semiconductors with different energetic *gap* between the velency and the conduction bands.
- The used semiconductors are different, provided that they have similar reticular constants (GaAs/AlGaAs, InAs/AlSb, InGaAS/InP)



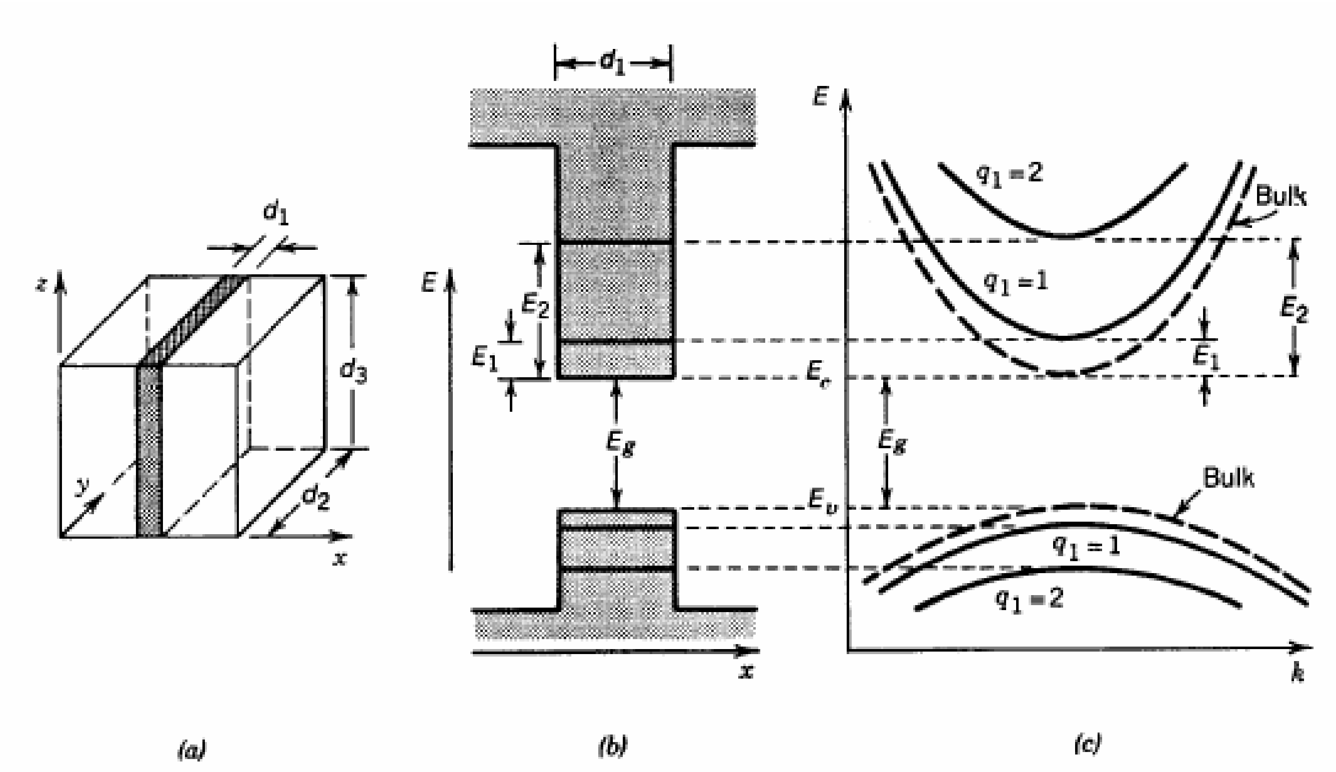
← GaAs no dopant

← $Ga_{1-x}Al_xAs$ “n” doped in Si

← Spacer no dopant

← Substrate

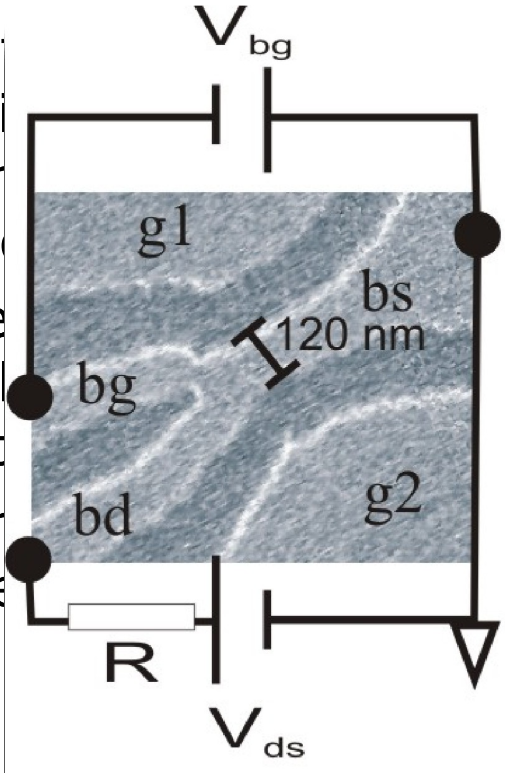
Charatteristics of the heterostructure (2)



(a) (b) (c)

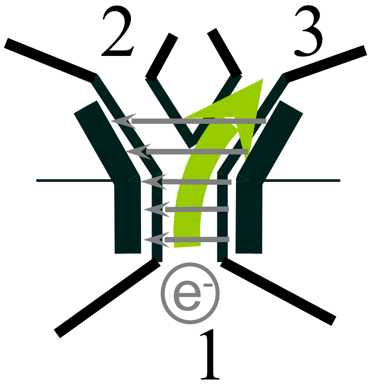
Fabrication

- The transis ron mobility are
  obtained wi , based on
  evaporatior chnique allows to
  obtain a se layers.
- Electron-be l wet-chemical
  etching witl $_2$ solution were
  used to obt he device.
- Next, 500 r ayers for ohmic
  contacts we annealed.



Electron Waveguide Y-Branch Switch (YBS)

T. Palm and L. Thylén, Appl. Phys. Lett. **60**, 237 (1992)



Single mode coherent mode of operation:

Envelope of electron wavefunction propagates to either drain depending on the direction of electric field across the branching region.

Required switching voltage in the branching region:

$$\Delta V_{switch} \approx \frac{\hbar}{e\tau_T}$$

- no thermal limit → promises extreme low-power consumption
- waveguide device → small is good
- monotonic response → tolerant to fabrication inaccuracies
- Drawback →low current operating condition means low low speed of circuits

Required switching voltage

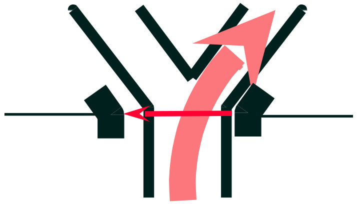
T. Palm, L. Thylen, O. Nilsson, C. Svensson, J. Appl. Phys. **74**, 687 (1993)

Required change in applied gate bias required to change the state of the YBS:

$$\Delta V_S^{YBS} \approx \frac{\square}{e\tau_T}$$

Example (GaAs):

- Sheet carrier concentration 4×10^{15} m^{-2}
- Interaction length 200 nm



→ Theoretically required switch voltage 1 mV

Contrast with the limit for a FET, that is 50 times higher at room-temperature:

$$\Delta V_S^{FET} = \log(10)\, {k_B T}/{e}$$

Sub-thermal switching in YBS just experimentally verified !

L. Worschech *et. al.*, private communication

Electron transport – Landauer-Büttiker formalism

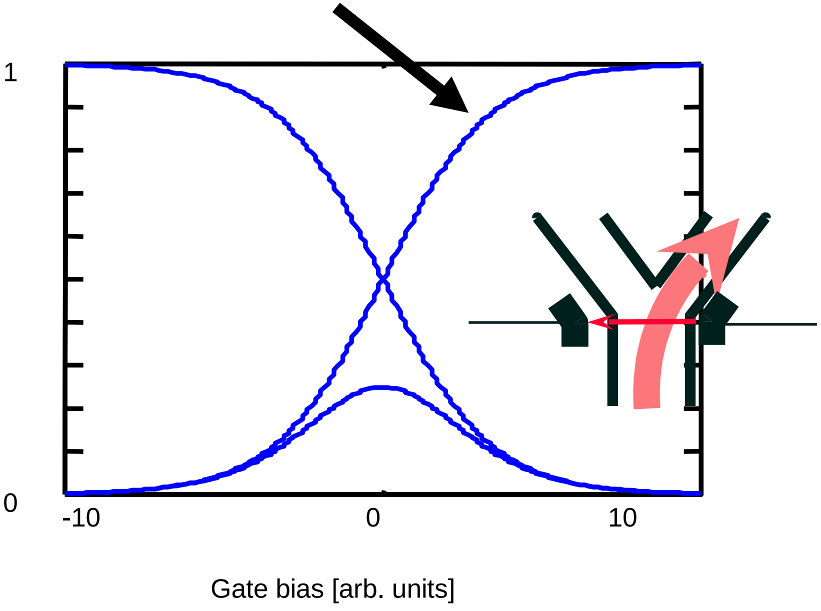
In coherent regime we can use the Landauer-Buttiker formalism to describe the electron transport:

Potential in the reservoirs

Identity matrix

Contact resistence

$$\bar{I}^r = \frac{1}{R_0}\left(\bar{E} - \bar{T}_Y\right)\bar{\mu}^r/(-e)$$


Transmission probability stem → right arm

Transmission probability:

$$\bar{T}_Y = \begin{pmatrix} 0 & \frac{1+\gamma}{2} & \frac{1-\gamma}{2} \\ \frac{1+\gamma}{2} & \frac{(1-\gamma)^2}{4} & \frac{1-\gamma^2}{4} \\ \frac{1-\gamma}{2} & \frac{1-\gamma^2}{4} & \frac{(1+\gamma)^2}{4} \end{pmatrix}$$

Switching parameter:

$$\gamma = \tanh\left(\frac{\eta_g \Delta V_g}{\Delta V_S}\right)$$

Space-charge effects switching

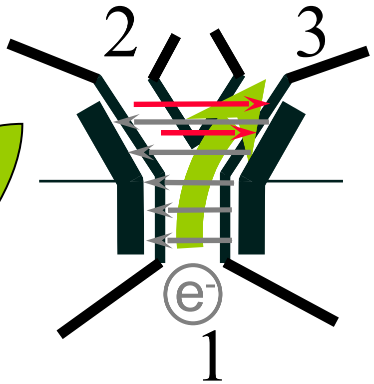
$$\bar{I}^r = \frac{1}{R_0}(\bar{E} - \bar{T}_Y)\bar{V}^r$$

$$\bar{T}_Y = \begin{pmatrix} 0 & \frac{1+\gamma}{2} & \frac{1-\gamma}{2} \\ \frac{1+\gamma}{2} & \frac{(1-\gamma)^2}{4} & \frac{1-\gamma^2}{4} \\ \frac{1-\gamma}{2} & \frac{1-\gamma^2}{4} & \frac{(1+\gamma)^2}{4} \end{pmatrix}$$

$$\gamma = \tanh\left(\frac{\eta_g \Delta V_g}{\Delta V_S}\right)$$

The Self-Gating Effect

J-O J. Wesström Phys. Rev. Lett. 82 2564 (1999)



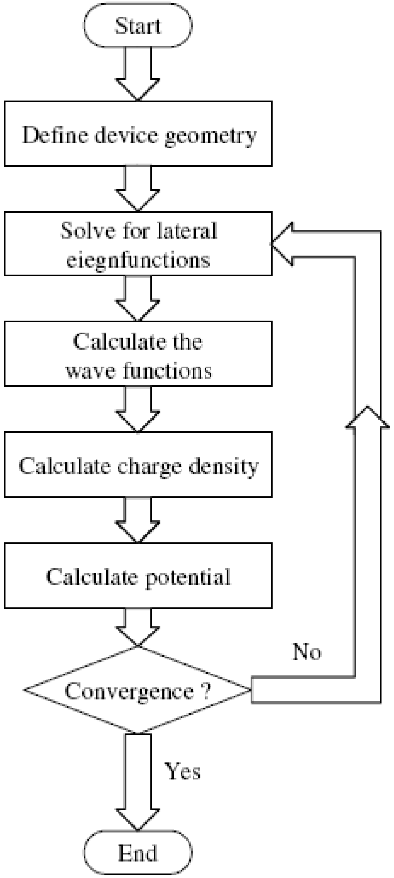
$$\gamma = \tanh\left[\frac{\eta_g \Delta V_g + \eta_{sg} \Delta W_{23}}{\Delta V_S}\right]$$

Self-gating effect

- Because of the contact resistence, a difference in current will create a difference in electrochemical potential $\Delta\mu_{23.}$ The current is directed to the waveguide with lower μ.
- $\Delta\mu_{23}$ becames the dominant effect
- The fenomenon creates a nonlinearity in the conductance between the three leads and it can be exploited studing the YBS without the gate potential.
- The result is *bistability.*

Nonlinear regime: self-consistent simulation

E. Forsberg, J. Appl. Phys, **93**, 5687 (2003)
E. Forsberg and J.-O. J. Wesström, Solid-State. Electron. **48**, 1147-1154 (2004).



Fully self-consistent simulation tool for simulations of electron waveguide devices developed.

$$\left(-\frac{\hbar^2}{2m^*}\nabla^2 + V(\mathbf{r})\right)\Psi(\mathbf{r},t) = i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t).$$

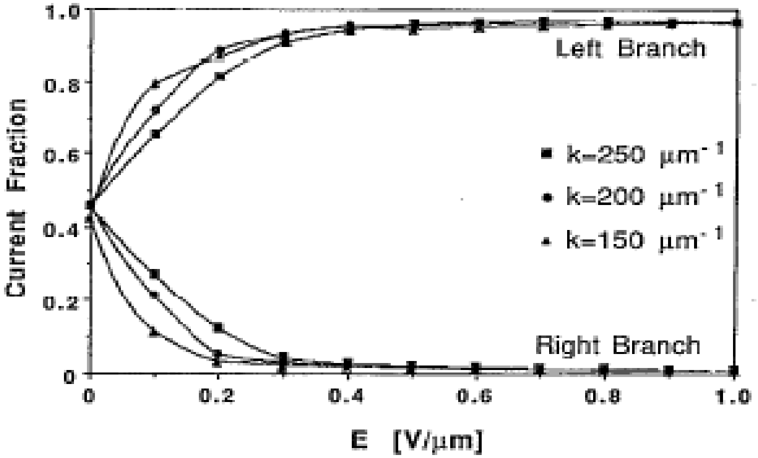
To solve the equation is needed only the potential in the 2D plane

$$\nabla^2\theta(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\epsilon_r\epsilon_0}$$ Poisson equation

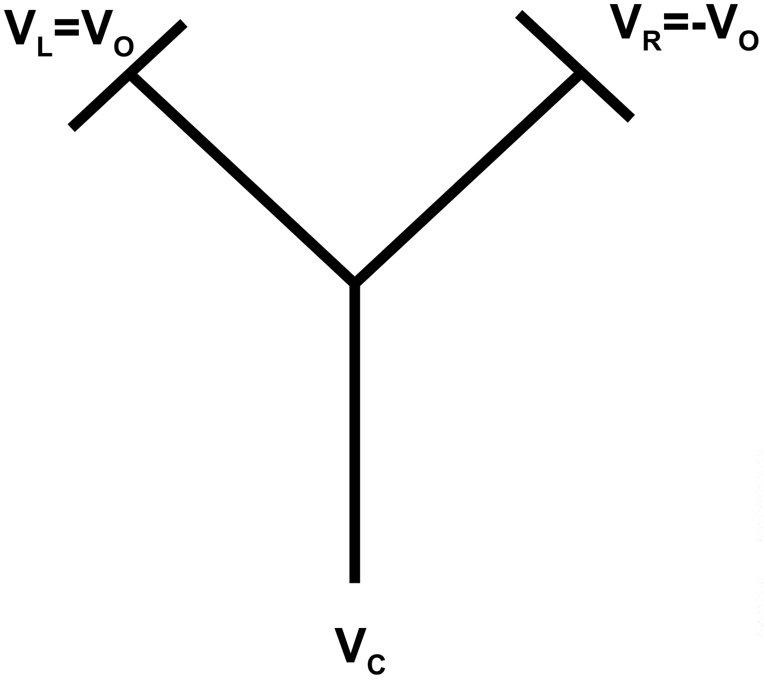
$$I_i = \frac{2e}{h}\left[N_i\mu_i - \sum_{jmn} T_{ij,mn}\mu_j\right],$$

Nonlinear regime

- It works as a multi-mode electron device
- The applied voltage is higher than the linear regime to ensure that the device is in a well defined state.
- The YBS has low sensitivity for velocity differences, so it can operate in the nonlinear regime without velocity filtering of the electrons



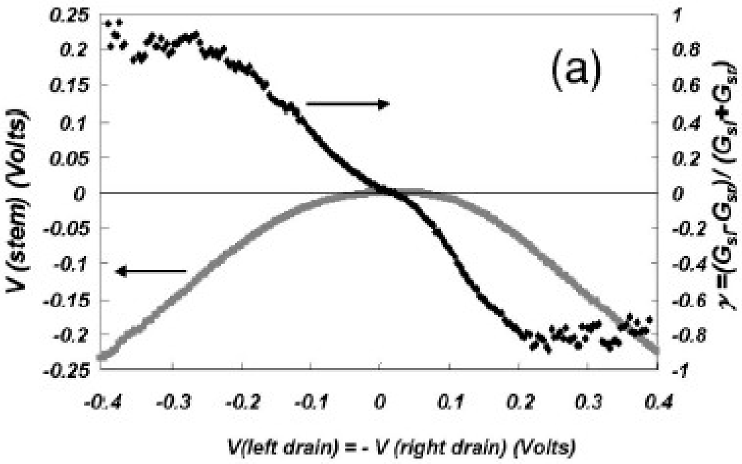
Nonlinear regime: ballistic switching mode



Classical: $V_C = 0$

Ballistic: $V_C = -\frac{1}{2}\alpha V_o^{\,2} + O\left(V_o^{\,4}\right)$

The α sign depend on the slope of the transmission



(1)

- Ballistic Transport
  - Branch width < Electron free wavelength

(1) PHYSICAL REVIEW B, Vol. 62, No.24, 15 DECEMBER 2000-II

Nonlinear regime: ballistic switching mode

- A more quantitative theory is based on the model for a YBS as a ballistic cavity, adiabatically connected via three point contacts to the reservoirs

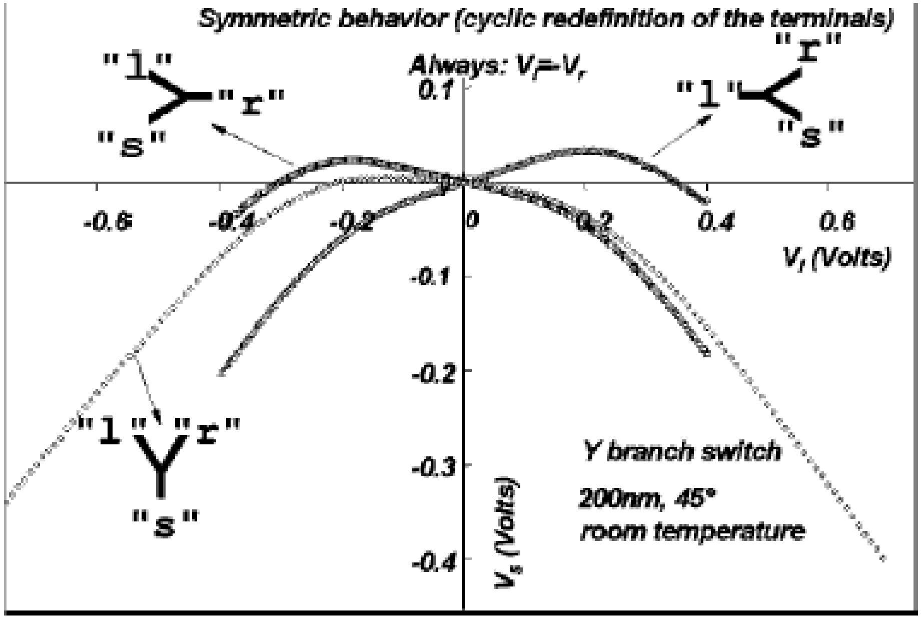
- For symmetric YBS, applying $+V$ and $-V$ to V_L and V_R will always result in negative V_c

- For asymmetric YBS,it is shown that V_c is negative for $/V/$ but it has to be greater than certain threshold

- It’s described with the “ballistic switching mode” and not with the “self-gating effect”

…at room temperature

- This reduction of the ballistic switching efficiency with increasing temperature and device size is correlated to mean-free-path L.
- The switching can be made more pronounceed even at room temperature by using higer bias



Summarize

YBS has three modes of operation

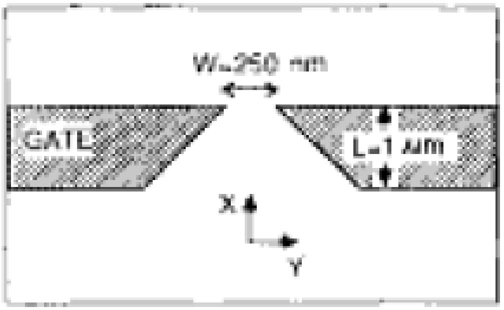
- Single mode transport
  - No thermal limit to switch voltage
- Self-gating operation
  - Switching based on space charge effects
  - Bi-stable mode of operation
  - (single mode operation)
- Ballistic switching
  - Multimode mode of operation
  - Room temperature operation demonstrated

Problems

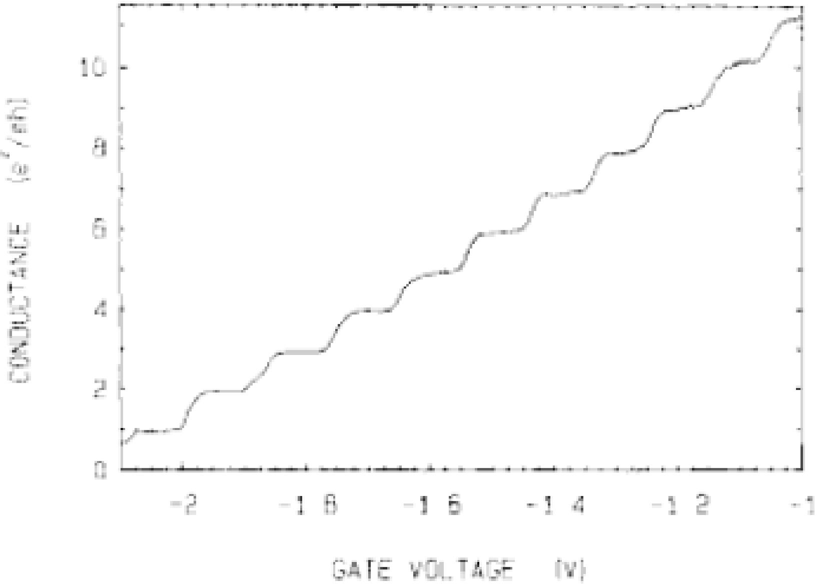
- The tip of the Y reflects the wave pocket, but it can be reduced below 8% adding a transverse field
- Increasing the brancing angle makes the Y more sensible to the different wave pocket velocities
- Scattering is caused by abrupt cheanges in the geometries and boundary roughness
- At low temperature, there are fluctuations in the transmission due to the electron scattering in the junction region
- The breakdown of the quantized conductance is also due to device length longer then the characteristic length of the fluctuations
- Random position of ionized-impurities in doped heterostructure give rise to a random potential. The fluctuations are relevants if the average density of electrons is lowered (from 2DEG to QW)

Quantized conductance

- Let’s assuming a narrow conductor. Due to the



GaAs/AlGaAs 2deg
$T = 0.6$ K
$n_{2d} = 3.6 \times 10^{11} / \mathrm{cm}^2$



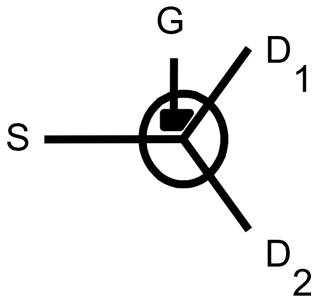
Van Wees *et al.*, PRL 60, 848 (1988)

- In the nonlinear regime, over a cartain voltage V_{BR}, the quantization breakdown

Also at room temperature is visible this effect, in the condition of $L<<l_e$

Logic Based on Y-branch Switches

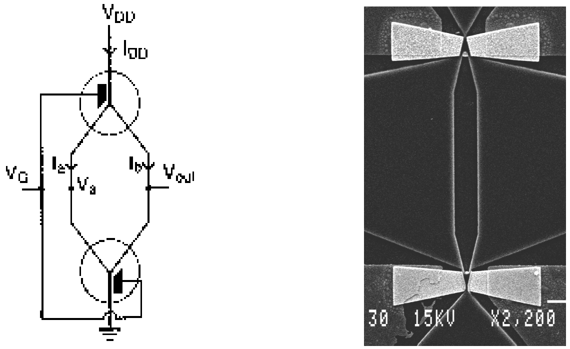
Electrical symbol and possible states



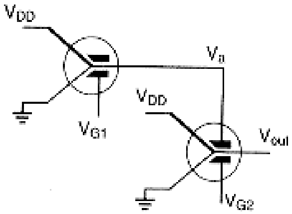
S	G	D_1	D_2
0	0	0	0
0	1	0	0
1	0	1	0
1	1	0	1

T. Palm and L. Thylén, J. Appl. Phys. **79** 8076 (1996)
E. Forsberg, unpublished

Inverter



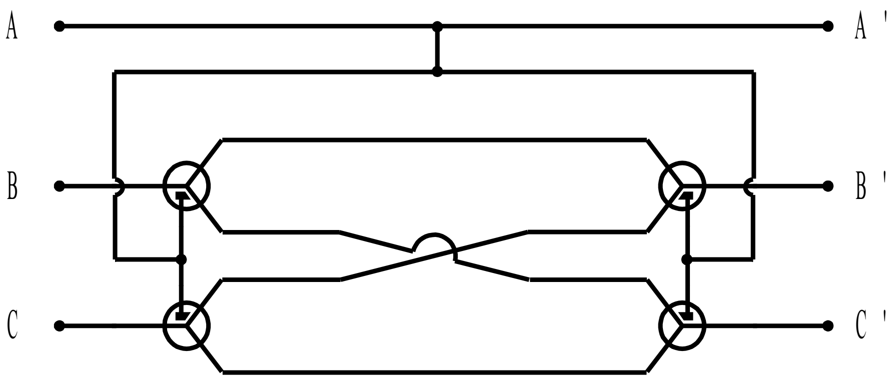
NAND gate using asymmetrical Y-branch switches



Reversible YBS logic

E. Forsberg, Nanotechnology **15**, 298 (2004).

ccNOT (Fredkin) gate



A	**B**	**C**	**A′**	**B′**	**C′**
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	1	1