Les potentialités de la nano-EBIC

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Outline

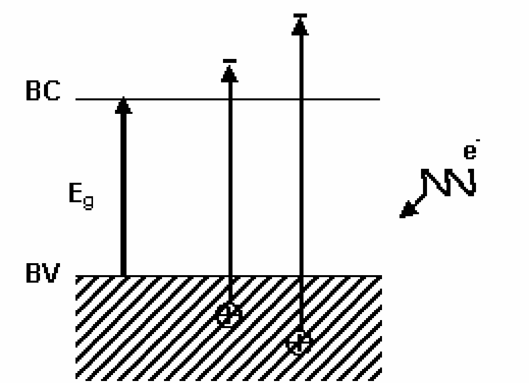
- Introduction
- Principes physiques de l’EBIC
- Qu’est-ce que la nano-EBIC ou EBIC en champ proche ?
- Instrumentation: combinaison AFM/MEB
- Exemples d’applications
- Conclusion

Introduction

EBIC: electron beam induced current

- Electron beam induced current (EBIC) method is a powerful characterization tool for the analysis of electronics devices
  - used for imaging the electrically active defects and heterogeneities in semiconductors
  - used for determining the diffusion length of minority carriers
  - used for estimating recombination velocities at grain boundaries and surfaces
- Resolution of EBIC imaging is chiefly limited by the lateral dimension of the energy dissipation volume, which depends on the material and primary electron beam energy
- Since the minimum feature sizes of electronic devices are continuously decreasing to enhance packing density and speed, and reduce power consumption there is a need for improved resolution
- That is the reason why we have developped a new technique that we call near-field EBIC or nano-EBIC

Principes physiques de l'EBIC

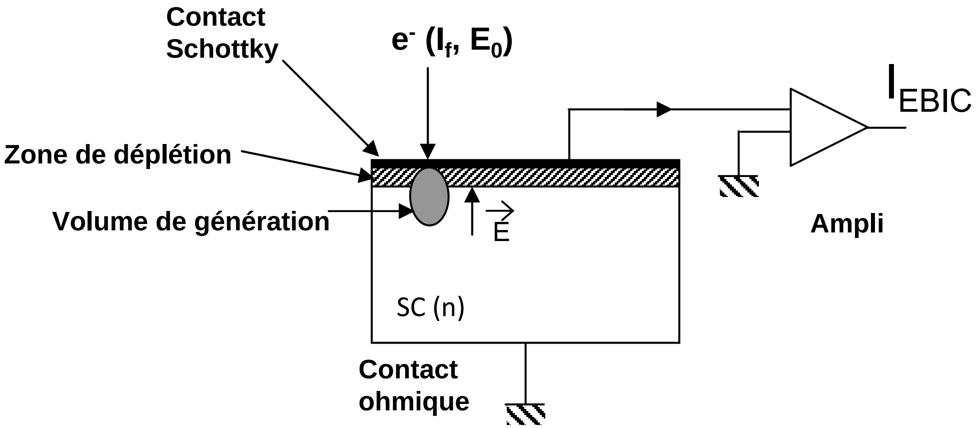


Mécanisme de création des paires électron-trou.

Processus possible si $E_0 > E_G$

Nombre de paires défini en terme de rendement quantique $Q = E_0/E_i$

E_i = Energie d'ionisation $\cong 3\ E_G$

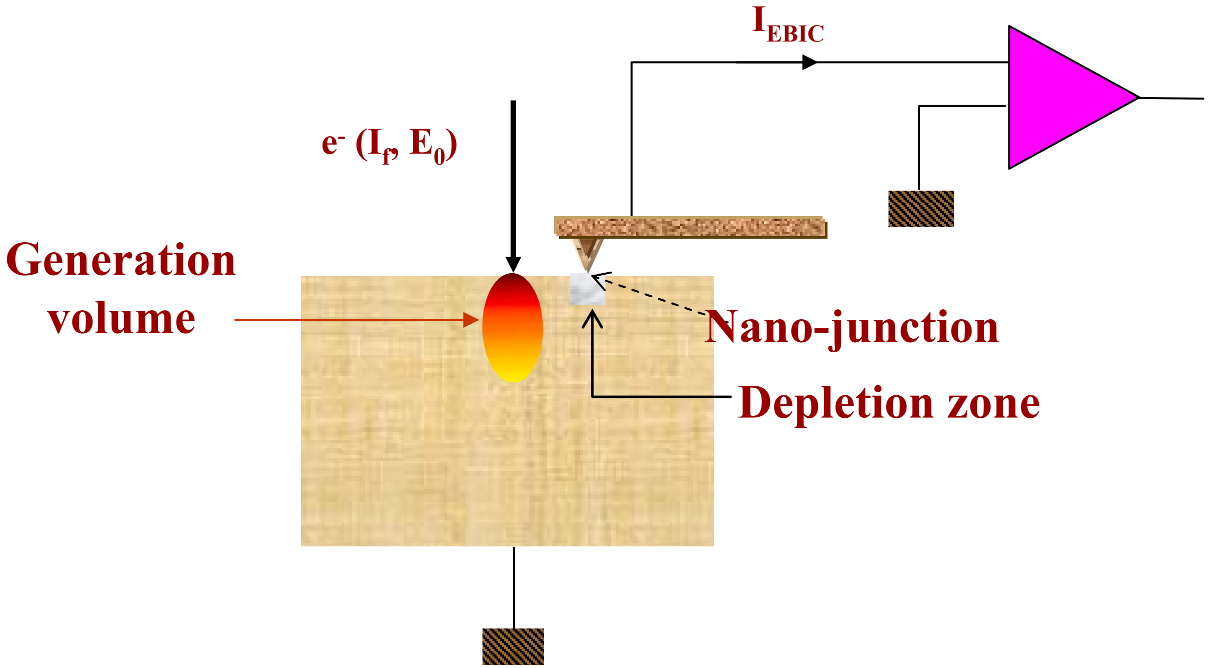


Principe Général de l'EBIC dans le cas d'une diode Schottky.

En absence de champ électrique diffusion et recombinaison des porteurs

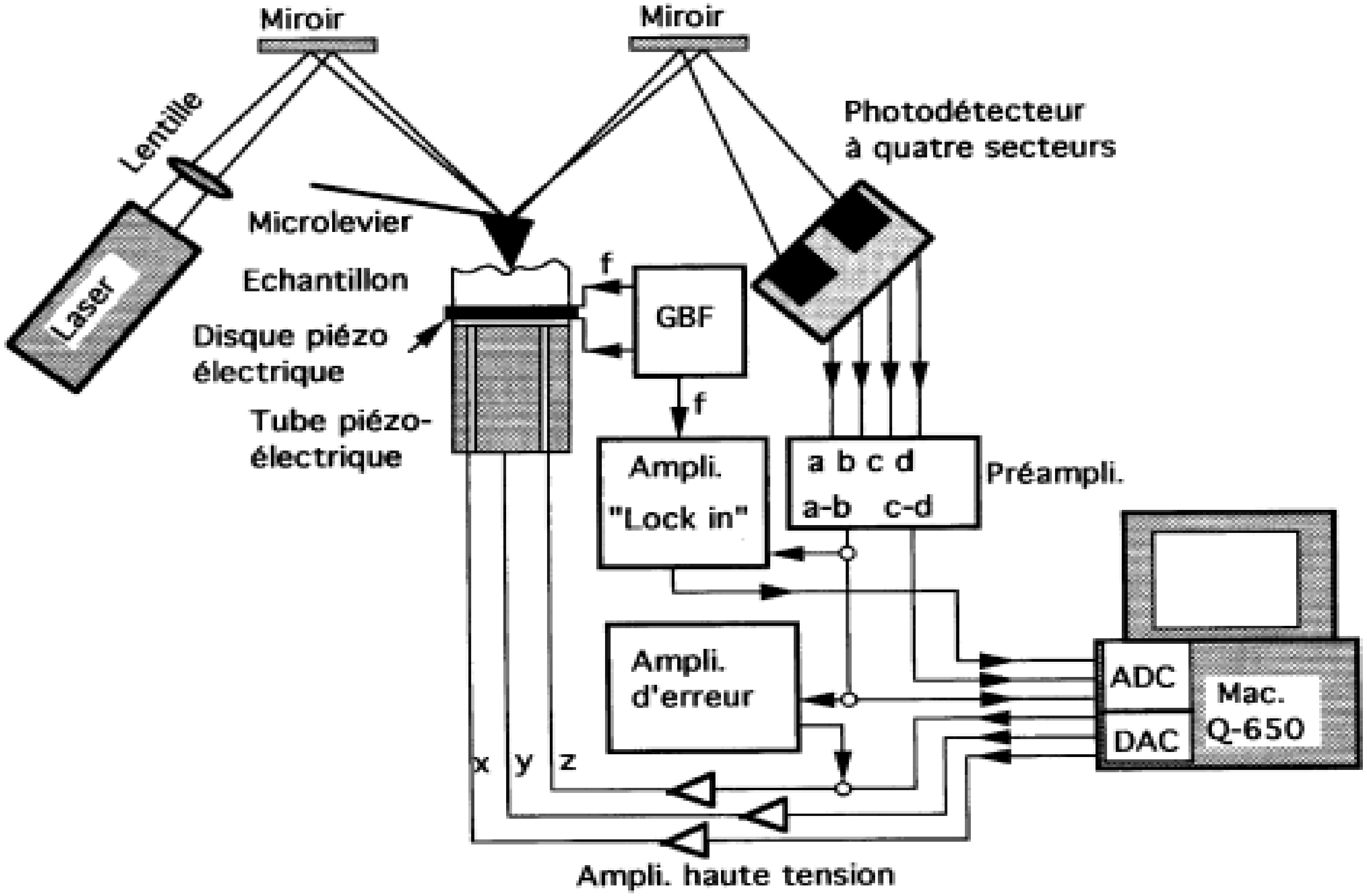
En présence de champ, l'excédent de porteurs minoritaires va se propager et former le courant $\mathbf{I_{EBIC}}$

Principle of nano-EBIC

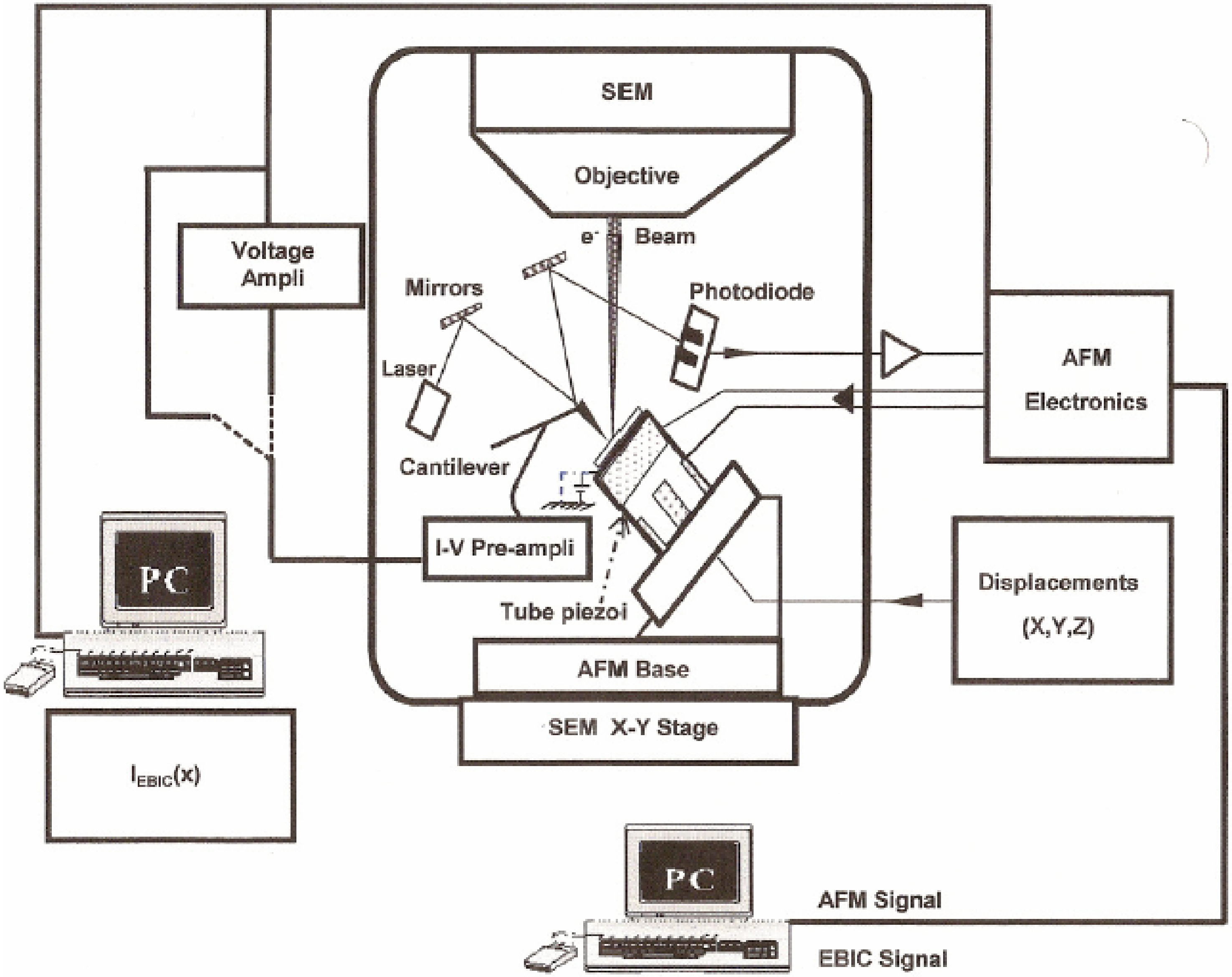


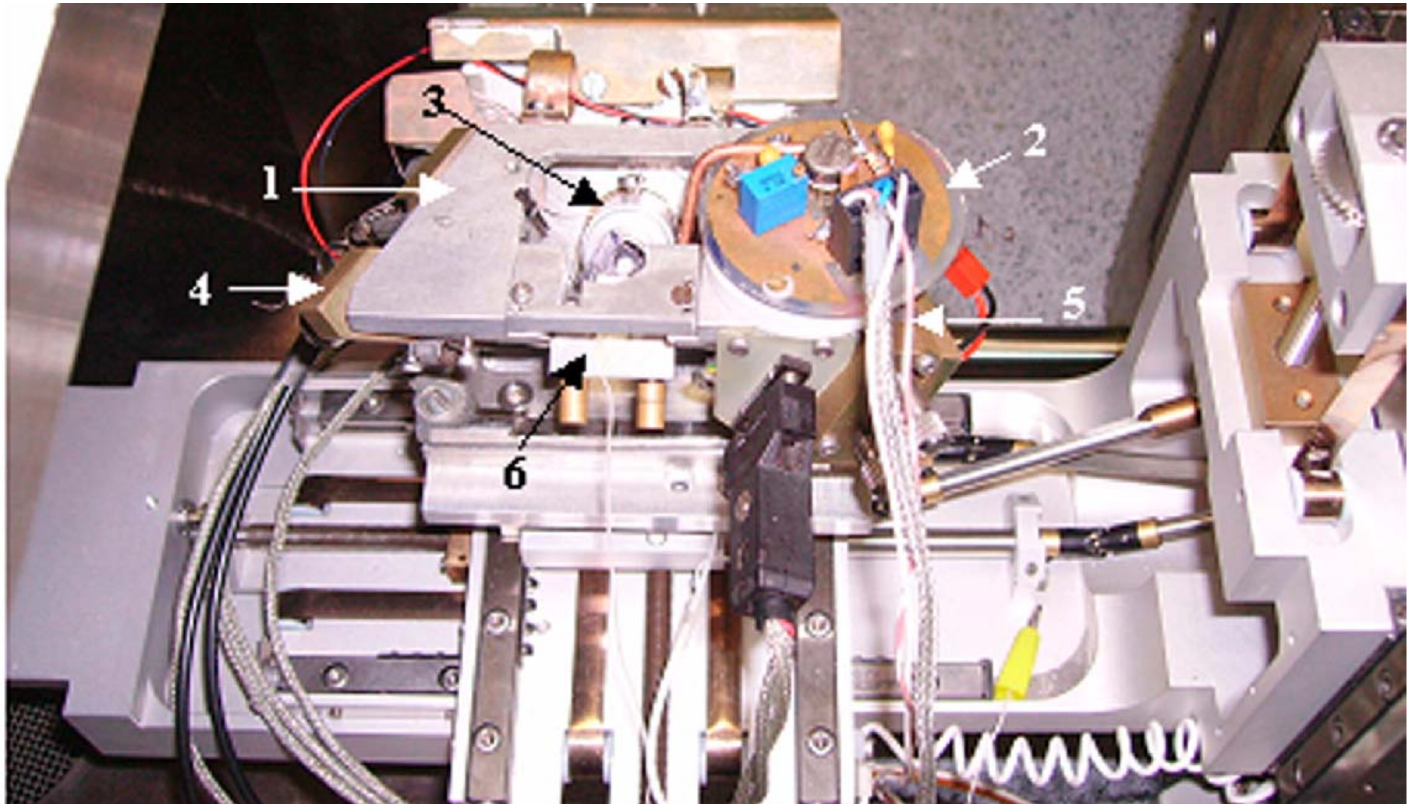
- **Resolution is not limited by the generation volume**
- **Resolution is limited by the dimension of the depletion zone ~ 10 nm**

Schematics of the AFM



The Combined AFM/SEM system





View of the AFM mounted inside the specimen chamber of the SEM

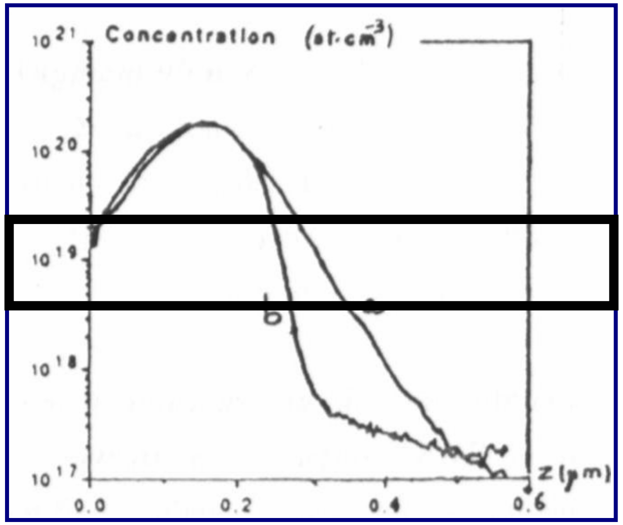
Application to shallow p^+-n junction

K. Smaali *et al*., Ultramicroscopy 108 (2008) 605.

Description of the p^+-n junction

- Preamorphisation of Si (n) substrate on 240 nm depth (Si^+, 150 keV, 5.10^{15} ion.cm^{-2})
- The p-doped layer is obtained with B^+ implantation (at 50 keV, 5. 10^{15} ion.cm^{-2})
- Rapid thermal annealing (< 1s, 1000 °C)

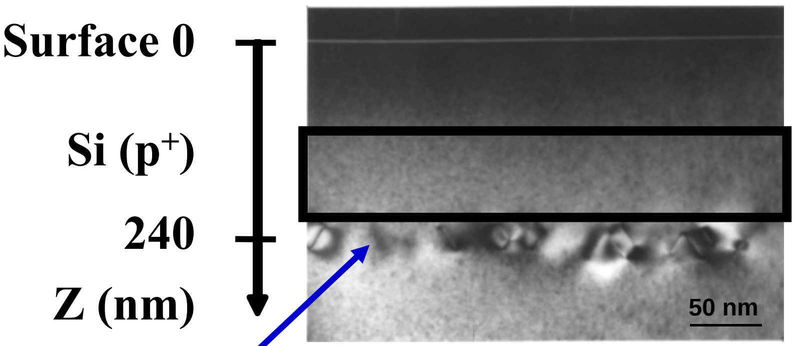
SIMS profile of p-doped layer
(50 keV, 5.10^{15} ions.cm^{-2})



(a) substrate without preamorphisation
(b) substrate after preamorphisation

Advantages

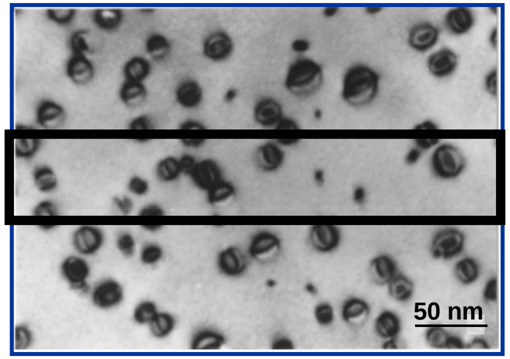
- Elimination of extended defects
- Avoid B^+ diffusion during activation step
- Reduce the doping profile to about 250 nm



End of range defects

Dark-field TEM Image
Cross-section

- **Dislocation loops :**
  Interstitial type
- **Non homogeneous**
  Distribution



TEM Image
Plane-view

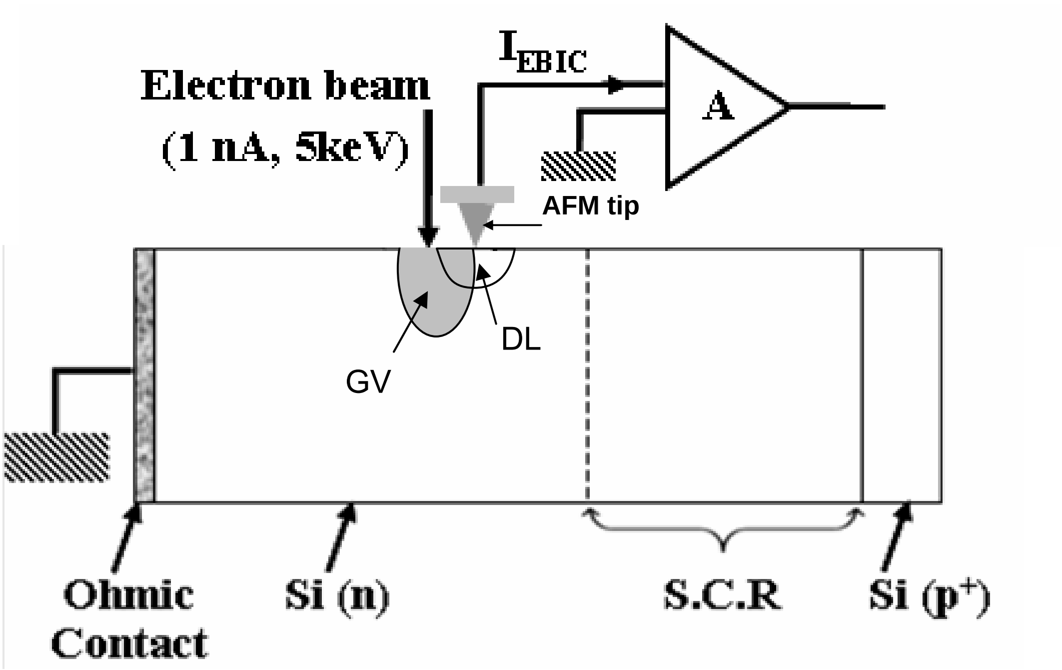
***End of Range* (EOR) defects**

Disadvantage

Formation of a band of defects

Study of the p^+-n junction in cross-section

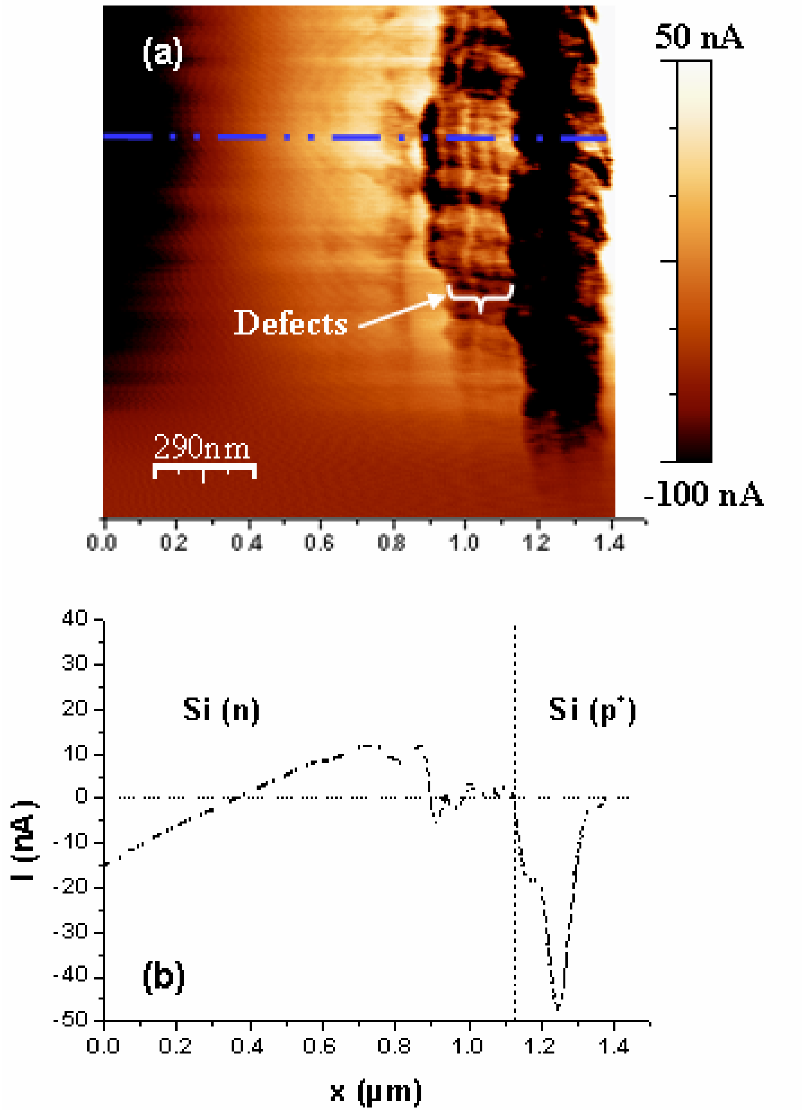
Set-up



-Existence of a small hemispherical Depletion layer (DL) at tip-surface contact which constitutes a MOS junction due to surface native oxide

- Space Charge Region (SCR) due to p-n junction

- When the tip is positioned above the SCR the carriers are subjected to 2 electric fields in opposite direction



- This example illustrates also the high-resolution of nano-EBIC

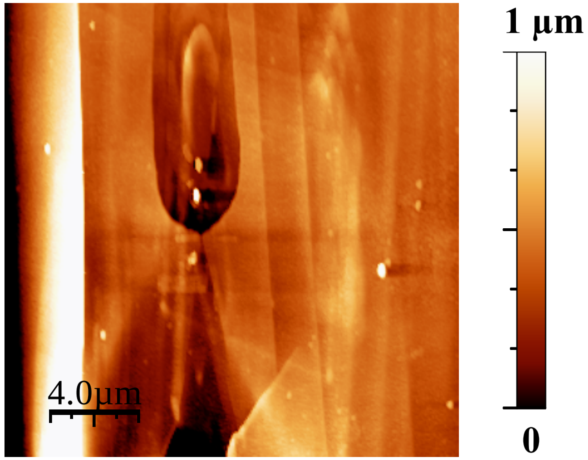
-Contrast variations are detected at the interface between n and p-doped regions, probably due to electrically active defects that are the interstitial dislocation loops revealed by TEM

- Resolution of about 20 nm

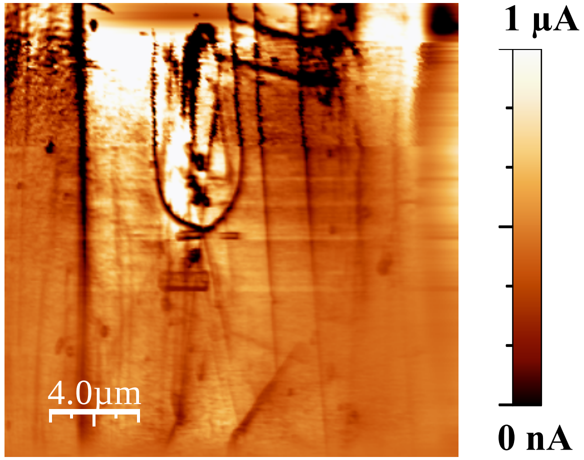
Application to III-V Heterostructures

K. Smaali and M. Troyon, Nanotechnology, 19 (2008) 155706

GaAs sample Indented with Berkovich diamond tip



Topography



EBIC image
I_f= 1 nA, E = 5 keV

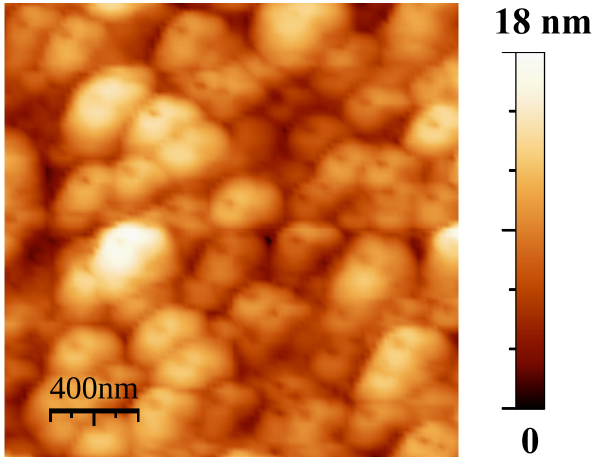
Dislocations or slip bands are clearly resolved in the EBIC image

Carriers are trapped on the dislocations due to non radiative recombination

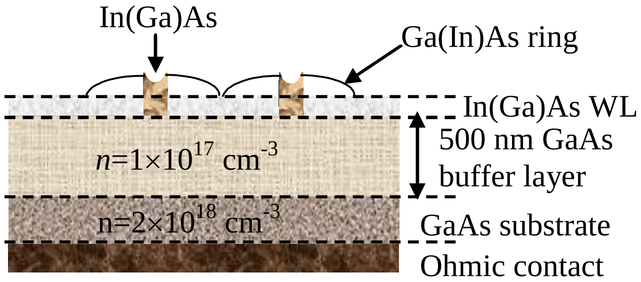
InAs/GaAS quantum dots

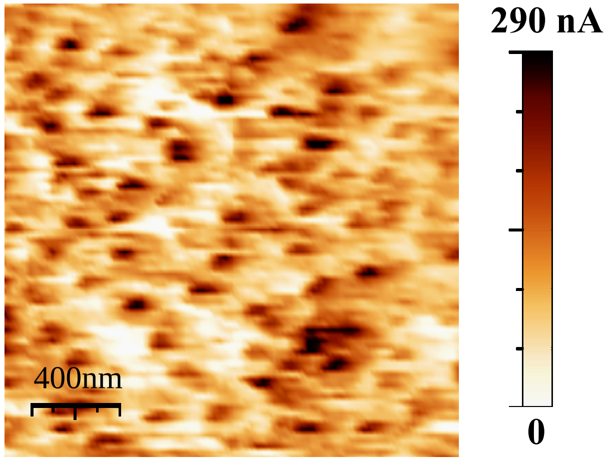
M. Troyon and K. Smaali, Nanotechnology, 19 (2008) 255709.

The QDs are grown by MBE and capped with a 5 nm thick GaAs layer



Topography

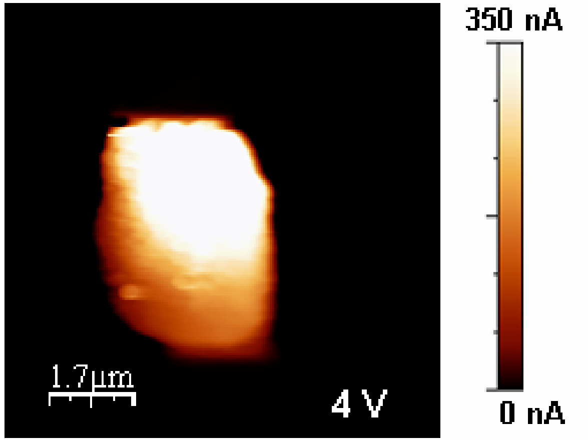




EBIC Image
I_f= 1 nA, E = 5 keV

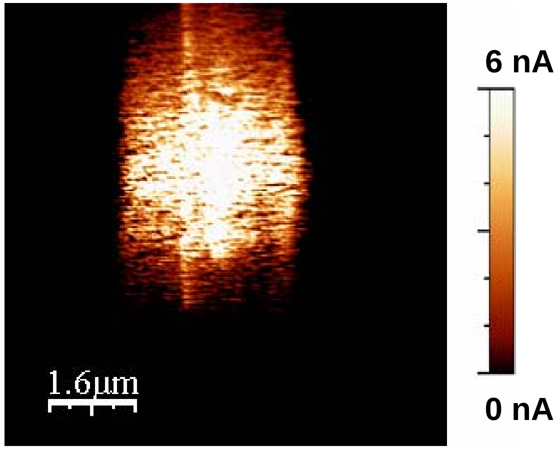
- **The cap-layer forms a ring-like structure around the QD**
- **The EBIC image shows that the current is very high in the middle of this nano-structure, which is the QD**

Writing-erasing-memory effects



C-AFM electric image of InAs/GaAs QD sample after electron irradiation of the central part at I = 1 nA and E = 5 keV.

64 hours later →



Bias voltage V= 0 V

WRITING

Holes are trapped in QDs and surface states during acquisition of the EBIC image (central part). Thanks to holes trapping, unpinning of the Fermi level occurs and then a C-AFM image can be obtained

ERASING

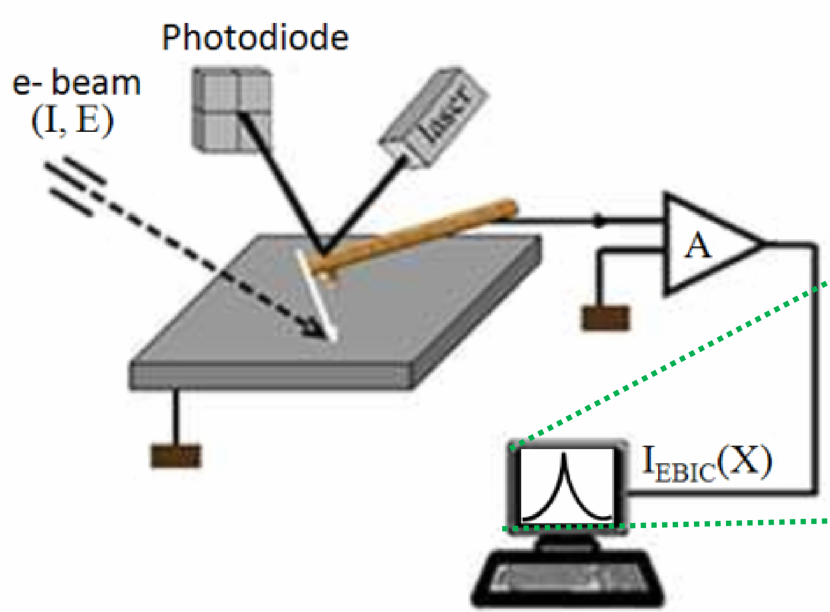
Erasing occurs when electron irradiation current is weak (I=60 pA). In these conditions surface recombination velocity is high and no induced current is generated. There is untrapping of the holes and thus Fermi level pinning, which hinders C-AFM image to be obtained even at V= 10 V.

MEMORY

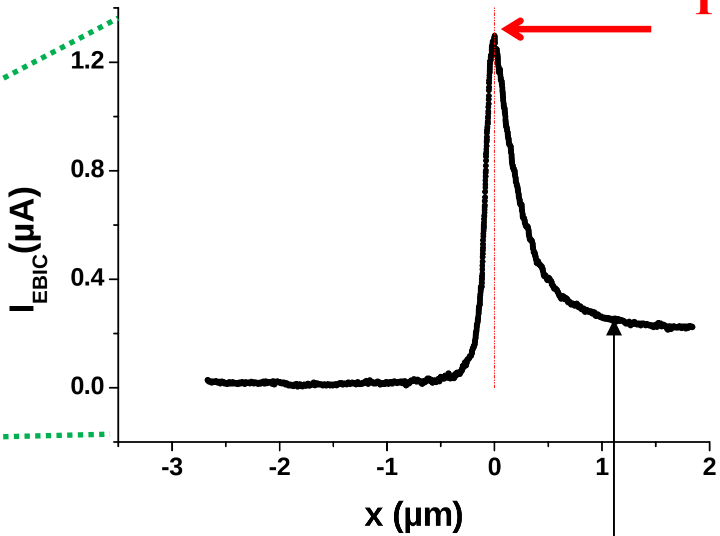
A strong current is still obtained after 64 hours waiting, evidencing a very efficient memory effect. The large charge retention time is explained by the presence of a thick depletion layer at the surface sample preventing the charges trapped in the QDs and the surface states from flowing towards the substrate.

Measurement of diffusion length

Experimental procedure



EBIC profile for GaAs
(I_f = 1 nA, E = 5 keV)



Position of the tip

Photon recycling due to photon reabsorption caused by radiative recombination

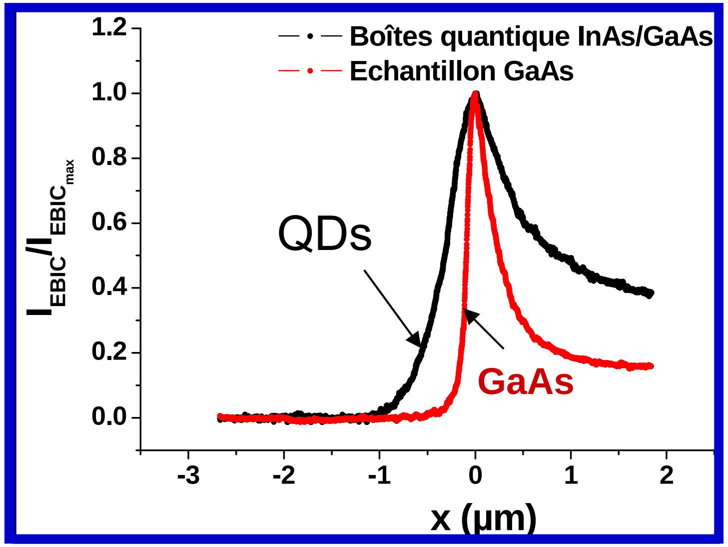
$I_{EBIC} \propto \exp(-x/L_{eff})$ ➡ L_{eff} = effective Diffusion length

$$(L_{eff})_Z^2 = L^2\{1-[s/(1+s)]\exp(-z/L)\}$$

$(L_{eff})_z$ is the effective diffusion length of the small volume at depth z

L is the bulk diffusion length and s = Sτ/L with S the surface recombination velocity and τ the carrier lifetime

Influence of the presence of QDs



GaAs reference sample ⇒ L=0.12µm

GaAs containing QDs ⇒ L=0.40 µm

InP reference sample ⇒ L=0.26µm

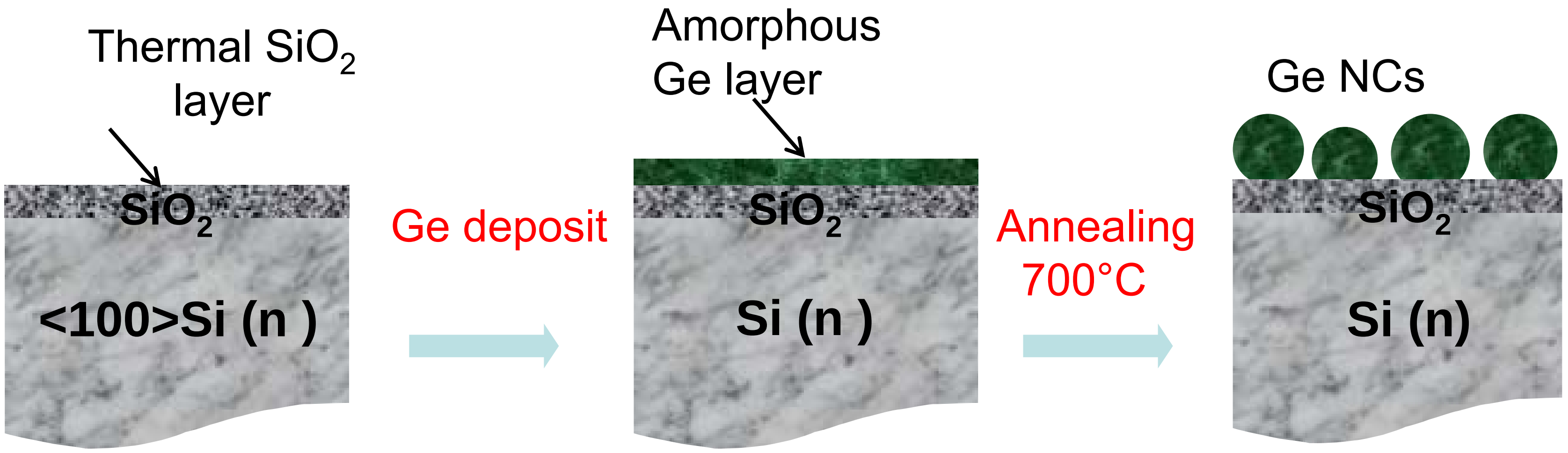
InP containing QDs ⇒ L=0.46 µm

➡ **Lateral exchange of carriers via the wetting layer because QDs and surface states are saturated**

Germanium nanocrystals grown on SiO_2

P.D.Szkutnik *et al*, Eur. Phys. J. Appl. Phys. 41 (2008) 103

Sample preparation



Thermal SiO_2 layer

SiO_2

<100>Si (n)

Ge deposit

Amorphous Ge layer

SiO_2

Si (n)

Annealing 700°C

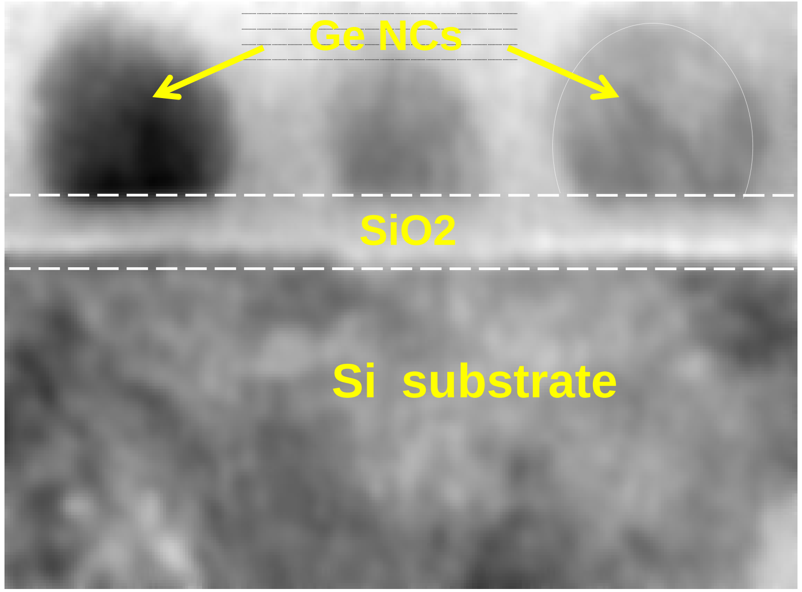
Ge NCs

SiO_2

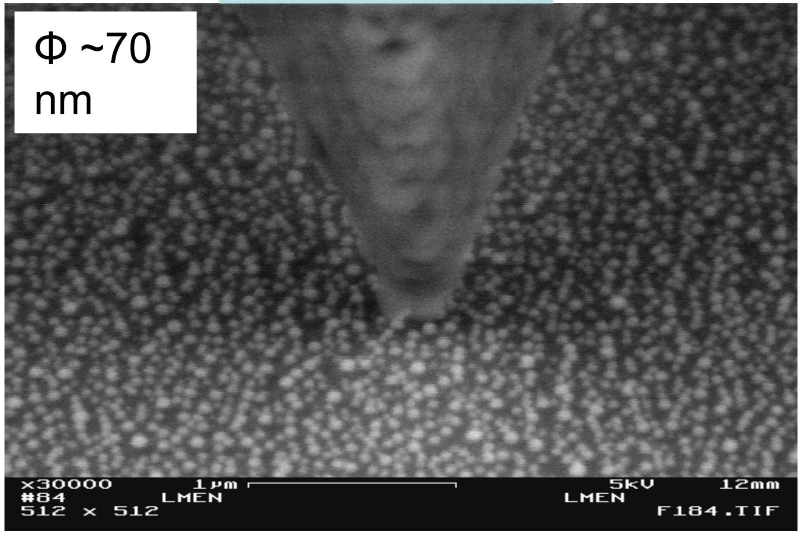
Si (n)

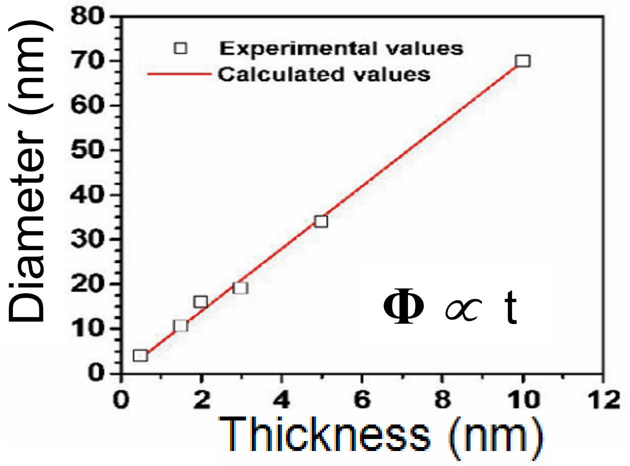
MBE chamber (10^{-11} torr)

TEM image

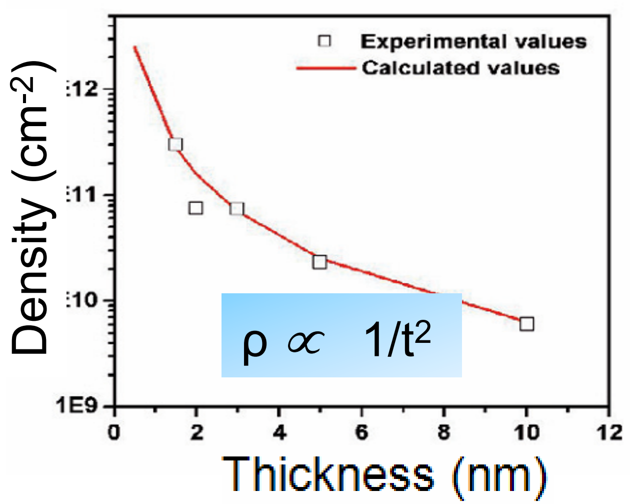


SEM image



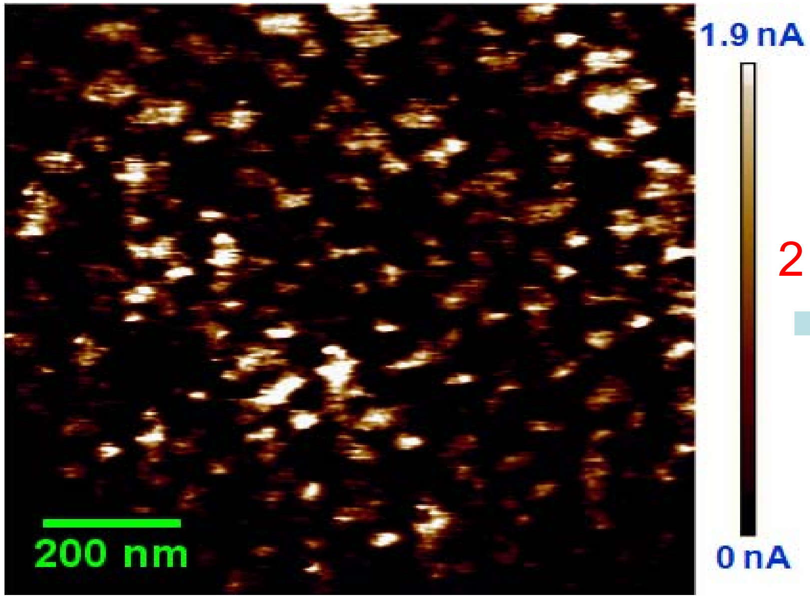


t = thickness of deposited Ge layer



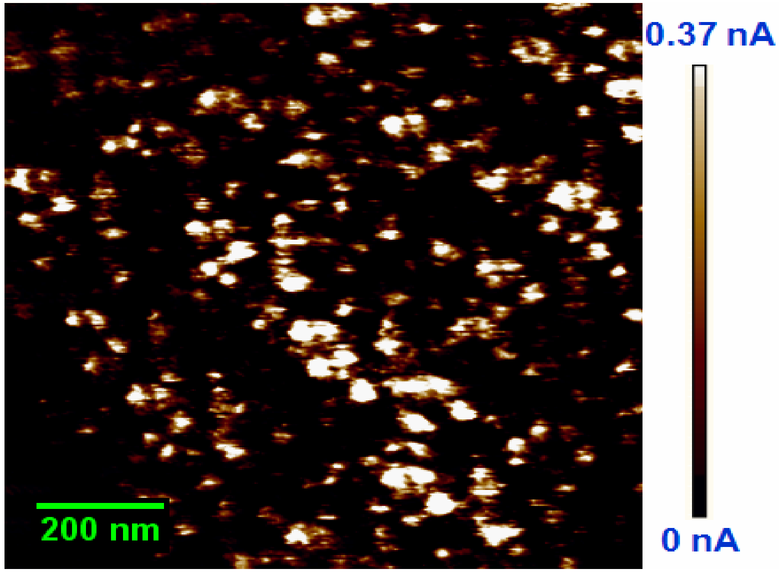
NEAR-FIELD EBIC

Memory effect



NF-EBIC (Ebeam = 5keV, V = 0V)

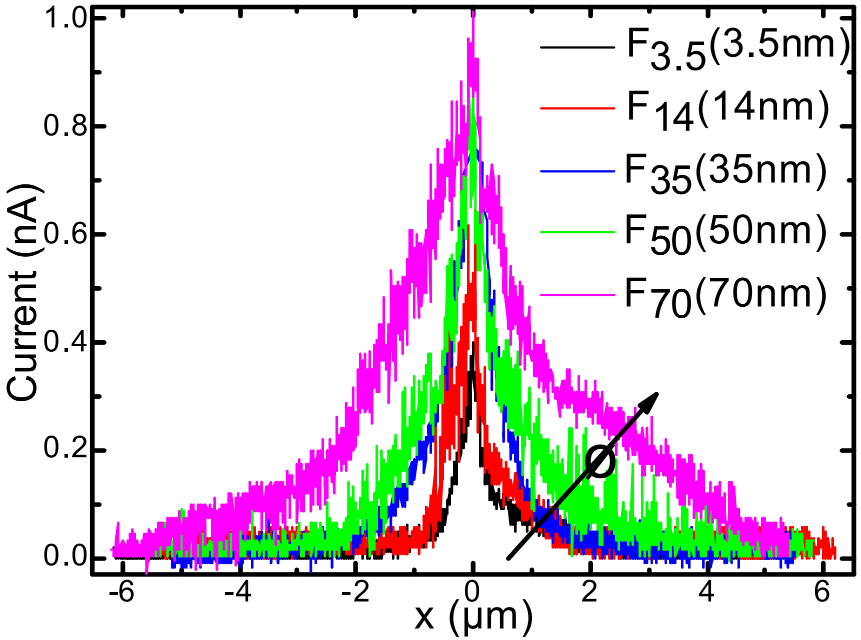
2 hours later



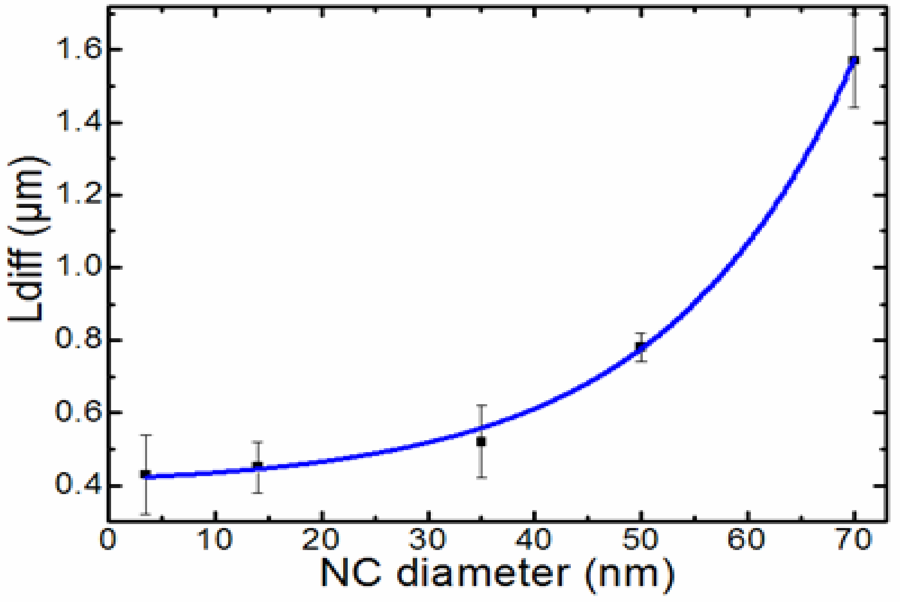
C-AFM (beam off, V = 0V)

Evidence of memory effect in the nanocrystals

Diffusion length variation with NC diameter



Current profiles



Exponential variation of Ldiff v.s NC diameter

The increase of diffusion length with the NC size is attributed to a stronger potential overlapping when the NC size increases, resulting in a lateral carrier exchange between the QDs.

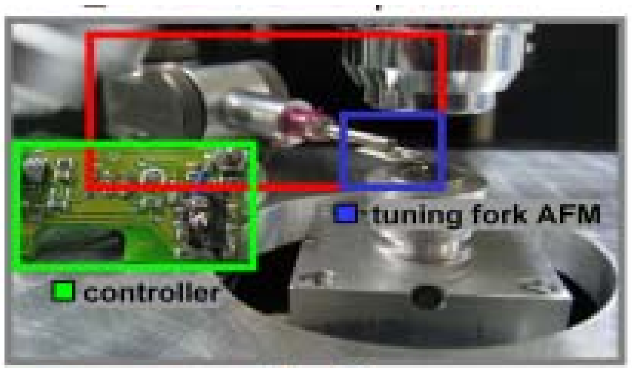
CONCLUSION

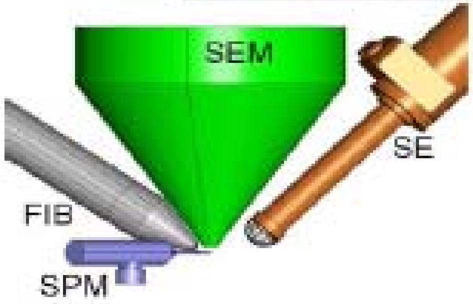
- The resolution of EBIC analysis can be strongly improved by combining AFM and SEM
- The resolution of near-field EBIC or nano-EBIC is limited by the size of the depletion layer created by AFM tip-surface contact, not by the generation volume
- We have seen through several examples that resolution is around 20 nm

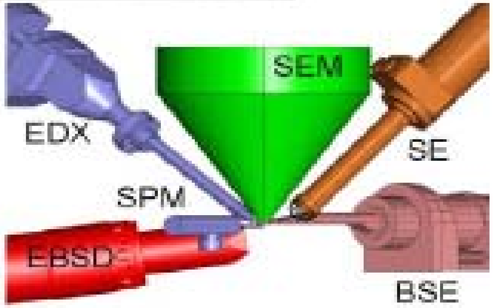
Acknowledgements

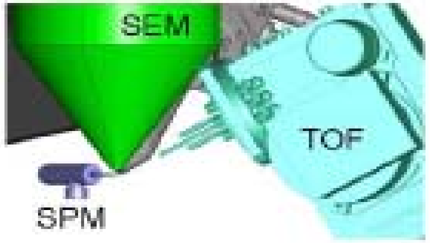
- G. Saint-Girons and A. Lemaître from the laboratory of Photonics and Nanostructures (Marcoussis, France)
- The Group of I. Berbézier, IM2NP, CNRS, Marseille, France
- This work was supported in part by the European Community FP7 program in the scope of the FIBLYS project under grant CP-TP 214042-2.

Projet 7ème PCRD :
« building an analyzing focused ion beam for nanotechnology »



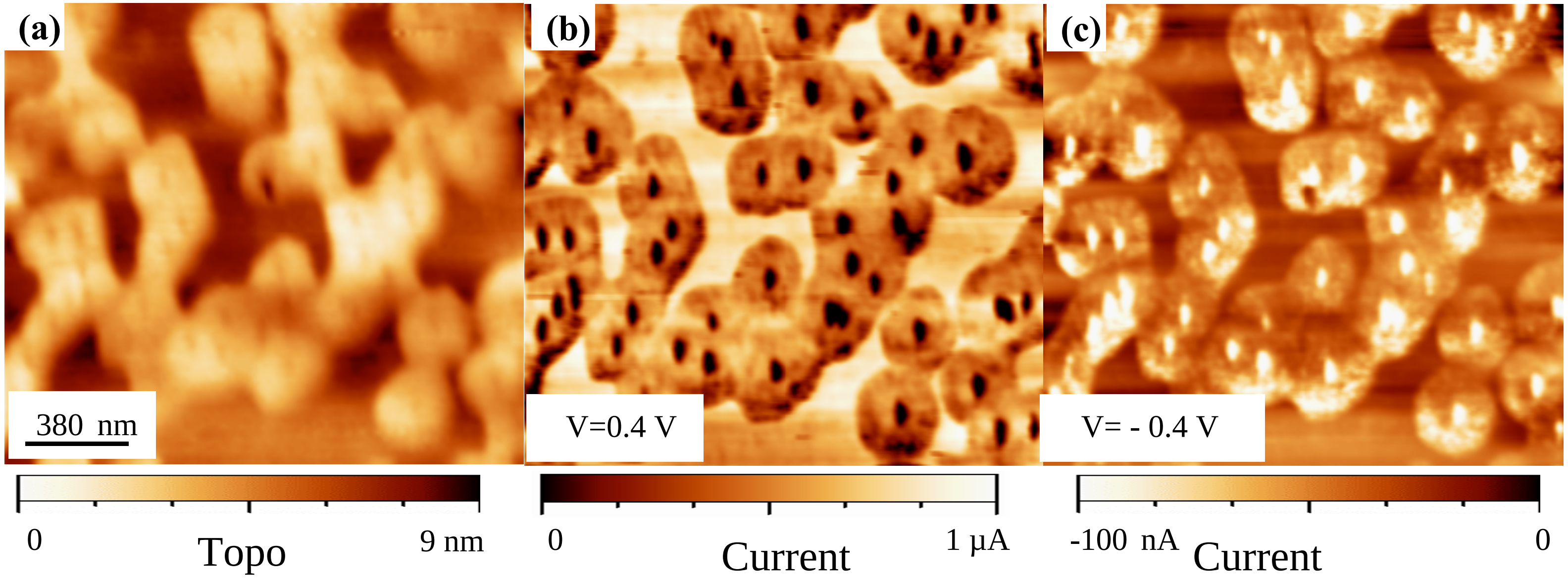


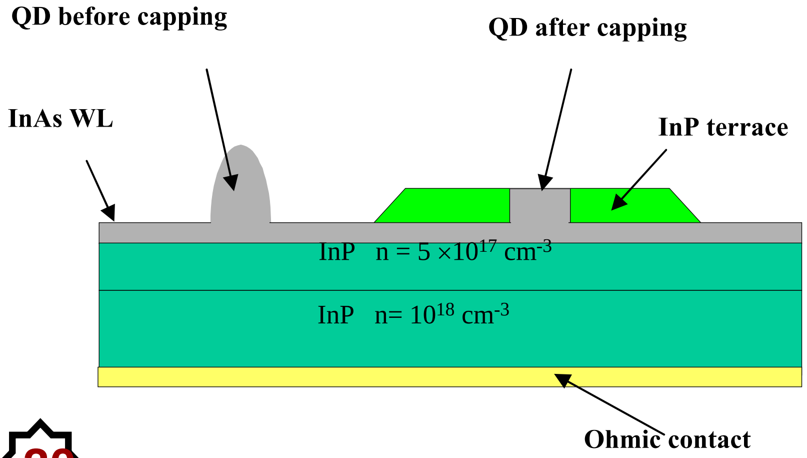




Conductive-AFM

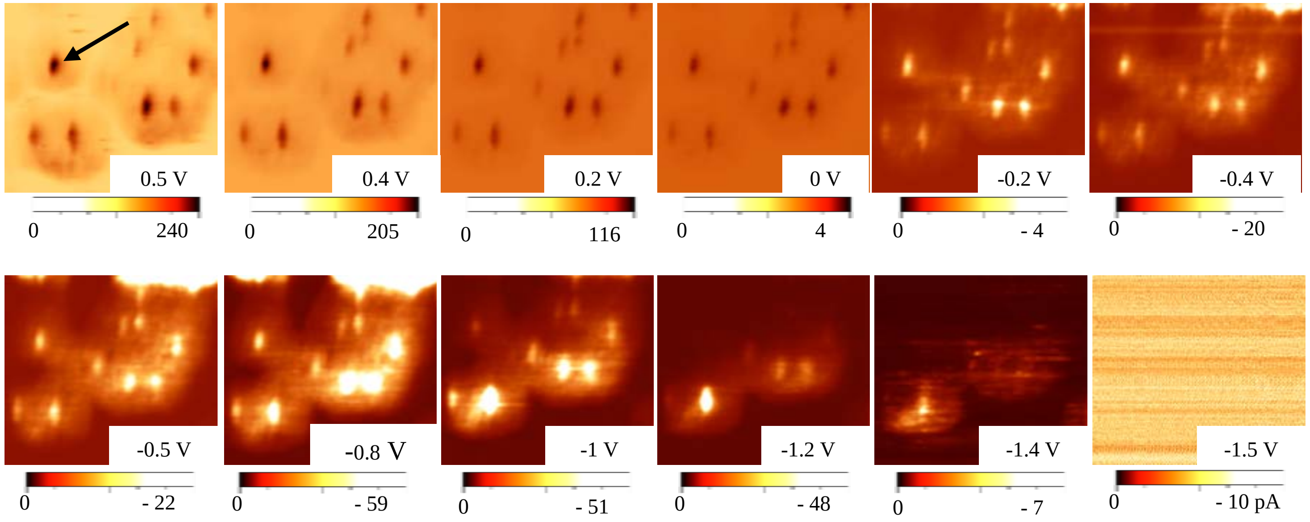
InAs QDs grown on InP(001) by MOVPE and covered with a 5 nm thick layer



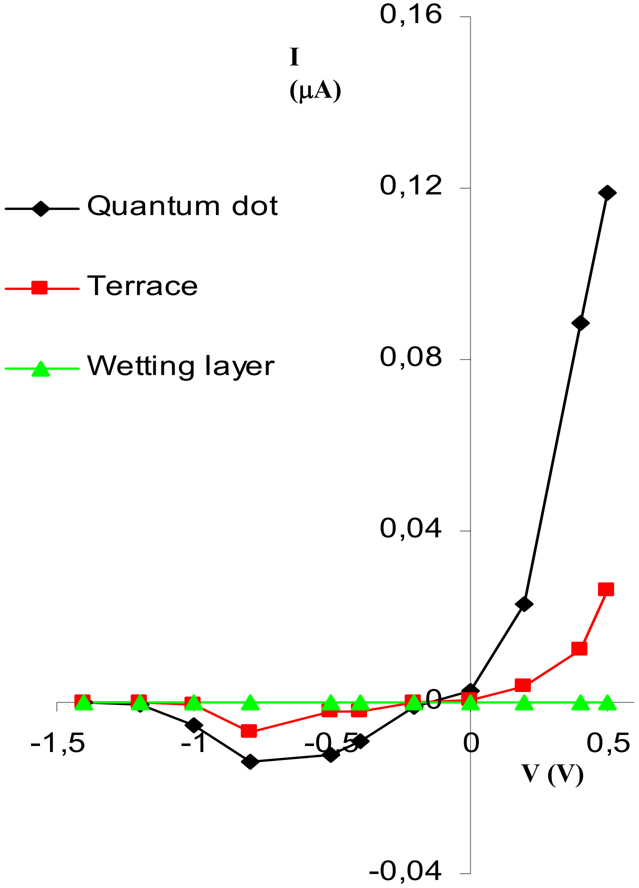


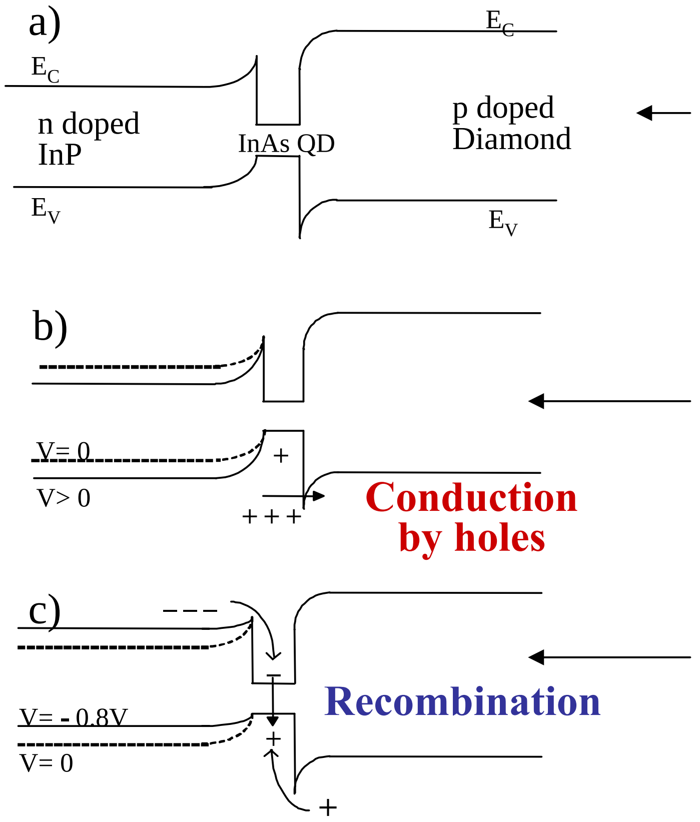
- The cap-layer does not entirely cover the surface but forms terraces around the dots
- 3 levels of current:
  - Very high on the dots
  - ~ 10 times less on the terrace
  - Null on the wetting layer

Electronic transport



I-V characteristics





Thermodynamic equilibrium

Forward polarisation

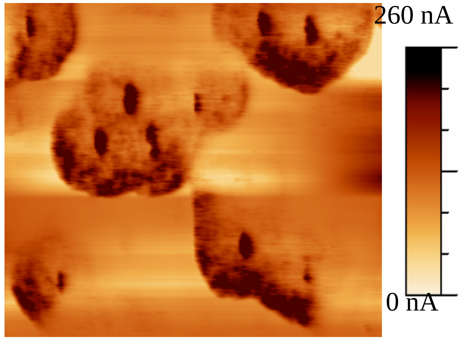
Conduction by holes

Reverse polarisation

Recombination

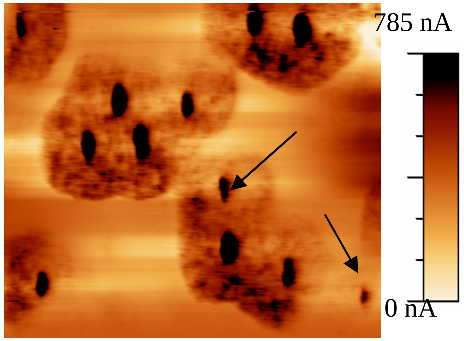
Writing-erasing

Memory effect



V=0.3 V

1rst image



V=0.3 V

2nd image

Current increases in the 2nd image

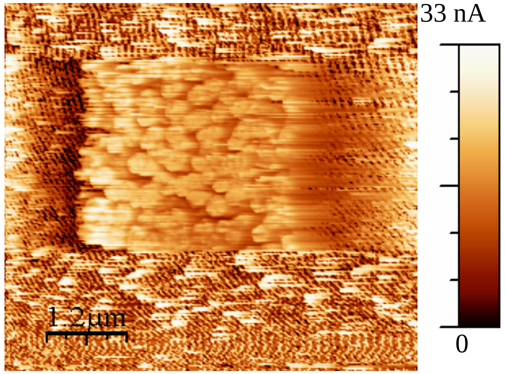


Image taken at 0.3 V

one hour after the

Central part at 0.8 V

QDs and terraces trap charges

Discharging occurs for negative bias