Field enhancement properties of nanotubes in a field emission set-up

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Framework

- ◇ Controversy in the mechanisms of emission
- ◇ Modeling of the polarization of CNT
  - · Resolution of the Poisson's equation
  - → Use of an atomic dipolar approximation
  - → The local field is computed with the Lippmann-Schwinger's equation
- ◇ β factor for SWNT:
  - ◦ evolution with the length
  - · evolution with the diameter
  - ◦ influence of the density
- ◇ β factor for MWNT
- ◇ Thanks and conclusions

◇ Flat panel displays:

- Low turn-on field
- Low sensitivity to the vacuum conditions
- High Brightness

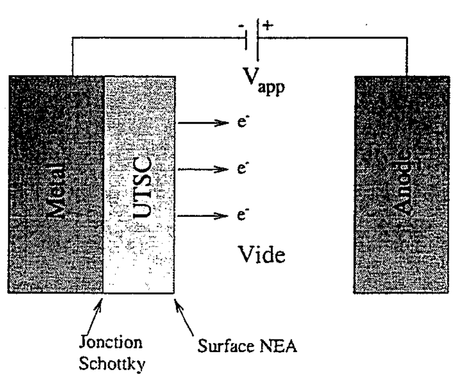
NEA materials:

Diamond type films:

- Emission from localized sites
- Emission mechanisns not well known

Ultra Thin SC film:

- Emission properties due to nanometer thickness
- Uniform emission
- Mechanism: Electronic injection → bending of the conduction band

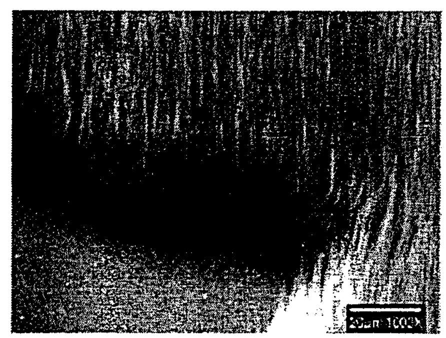


Vu Thien Binh, Adessi, PRL **85** *(2000)*

Carbone nanotubes:

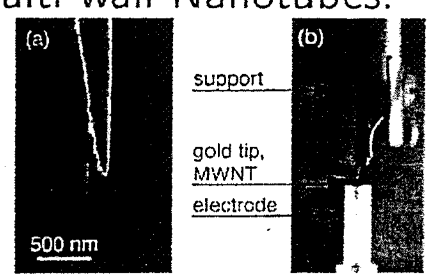
- turn-on field ≤ 1 V/μm
- Prototype of display already achieved

Nanotubes forest:



Z. F. Ren, Science **282** *(1998)*

Multi-wall Nanotubes:



J.-M. Bonard, Appl. Phys. A **69** *(1999)*

Mechanisms of emission

The mechanism leading to the electronic emission at low field is not well understood

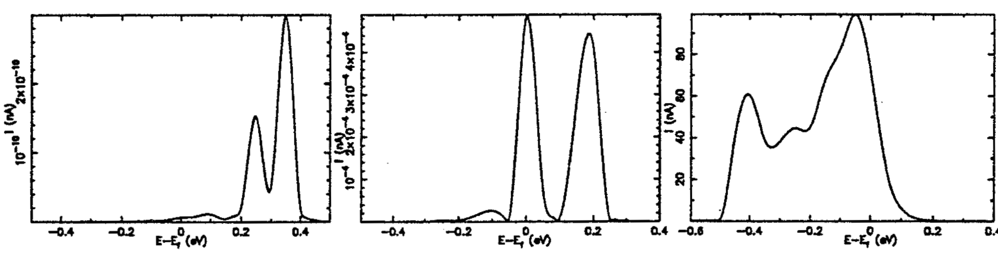
⇒Several phenomena are suspected to be involved

- o Enhancement of the applied field:
  - → Polarization phenomenon
  - → Localized space charge
- o Implication of localized states at the end of the nanotubes

- Uniform and atomic descriptions lead to contradictory results
- Is Fowler-Nordheim still valid?

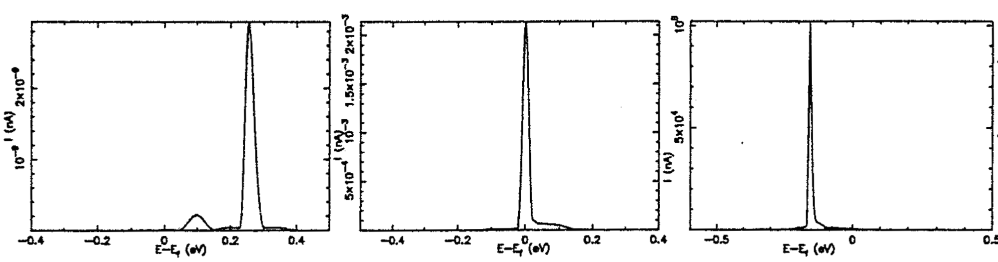
Energy Distributions

$E = 0.15\ V/$ Å	$E = 0.20\ V/$ Å	$E = 0.30\ V/$ Å
$I_M = 3 \times 10^{-10}$ nA	$I_M = 5 \times 10^{-4}$ nA	$I_M = 100$ nA



(5,5)

$I_M = 3 \times 10^{-9}$ nA	$I_M = 2 \times 10^{-3}$ nA	$I_M = 10^5$ nA



(10,0)

Theoretical background

- ◇ Aim: Compute electrostatic field near nanotube's end
- ◇ Model: Atomic dipoles and perfect metal

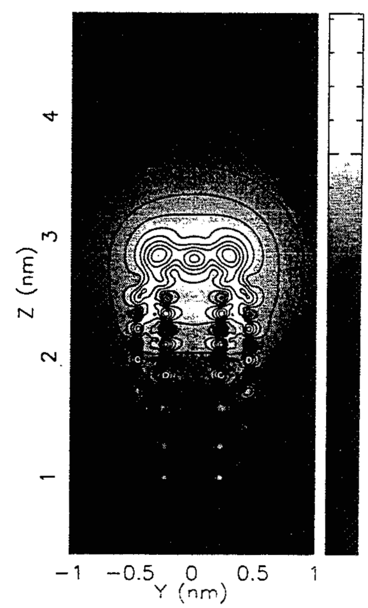
⇒ Self-consistent resolution of Maxwell-Gauss's law:

$$\vec{\nabla}_{\vec{r}} \cdot \vec{E}(\vec{r}) = -\frac{1}{\epsilon_0}\vec{\nabla} \cdot \vec{P} = \vec{\nabla}_{\vec{r}} \cdot \left[\sum_{j=1}^{N_{at}} \overleftrightarrow{\alpha_j}\,\delta(\vec{r} - \vec{r}_j)\vec{E}(\vec{r})\right]$$

⇒ $\vec{E}(\vec{r})$ solution of the Lippmann-Schwinger's equation:

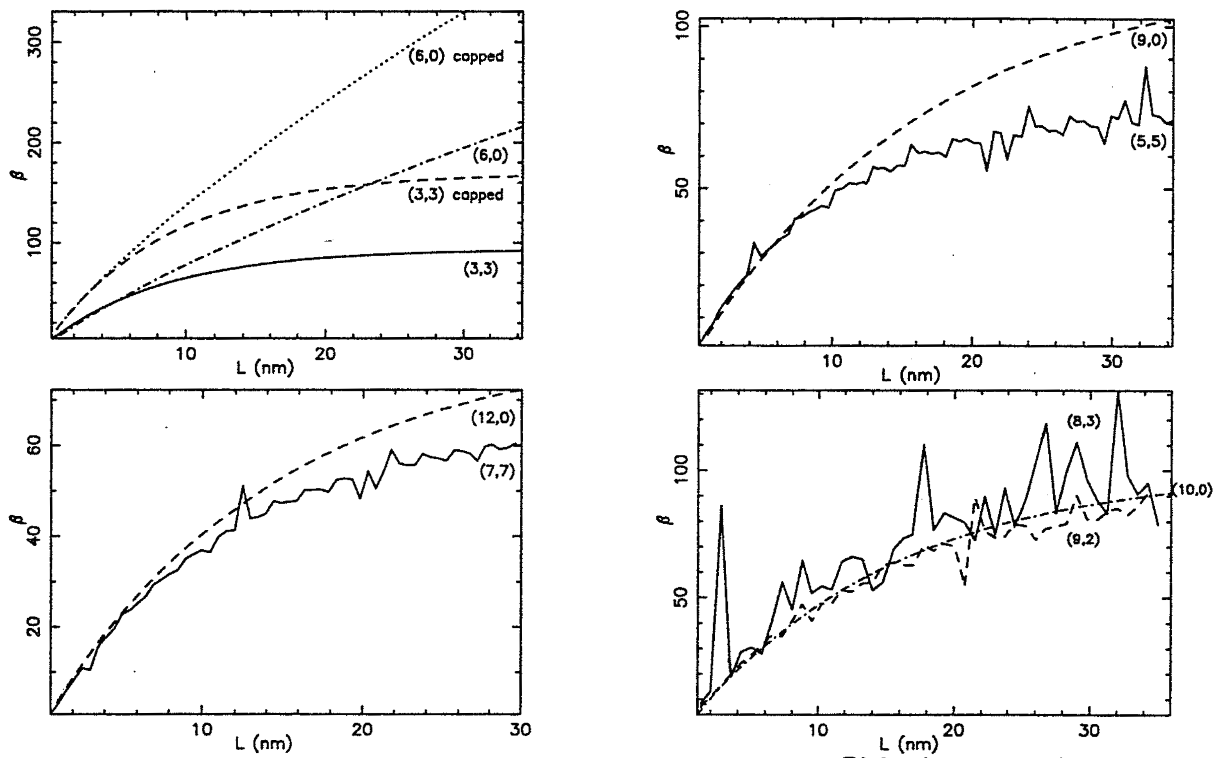
$$\vec{E}(\vec{r}) = \vec{E}_0(\vec{r}) + \sum_{j=1}^{N_{at}} \overleftrightarrow{S_0}(\vec{r}, \vec{r}_j) \cdot \overleftrightarrow{\alpha_j} \cdot \vec{E}(\vec{r}_j)$$

◇ Local field → $\beta = \frac{E_{loc}}{E_{app}} = \frac{Max(E_Z)}{E_0}$



Polarization potential
(5,5) capped nanotube

Single wall nanotubes



Chiral nanotubes

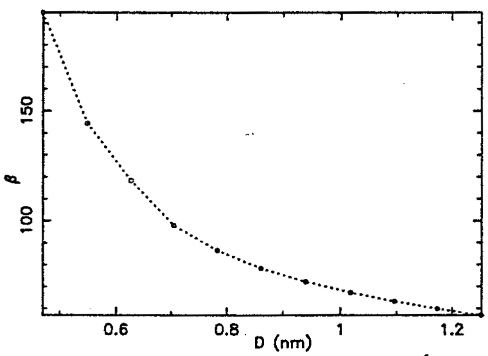
general trend:

$$\beta(L) = L \times \left[a_0 + a_1 \ln(L) + a_2 \ln^2(L) + \ldots\right]$$

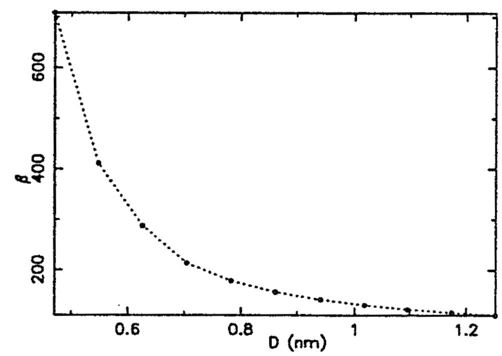
- ◇ Saturation of the β factor with the length
- ◇ Saturation sets up faster for (n,n)
- ◇ The caps improve the β factor but do not modify the general trend
- ◇ No significant influence of the chiral angle
- ◇ Extrapolation for a length of 1 μm: (6,0) capped $\rightarrow \beta \simeq 1100$

Variation with the diameter

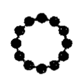
$L = 30$ nm



$L = 1\ \mu$m (extrapolated)



(n,0) nanotubes



(6,0)
$D = 0.47$ nm

(11,0)
$D = 0.86$ nm

(16,0)
$D = 1.25$ nm

◇ Variation law:

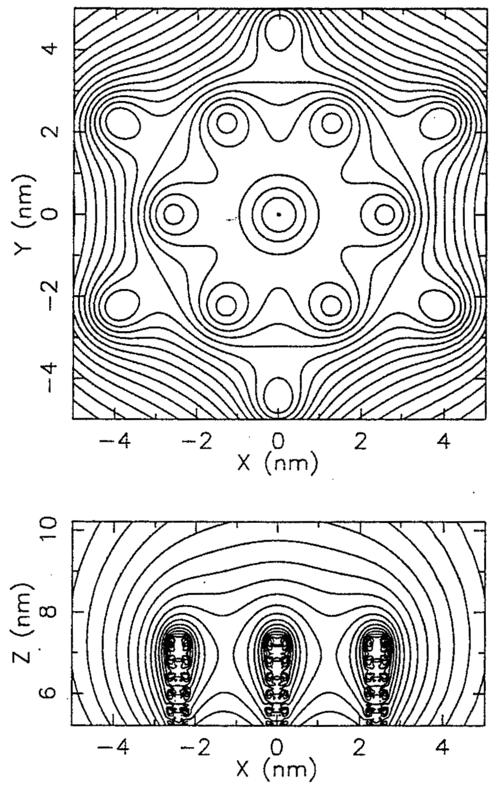
$$\beta(D) = a_0 + \frac{a_1}{D} + \frac{a_2}{D^2} + \frac{a_3}{D^3} + \dots$$

◇ $\beta \geq 1000$ can only be obtained with $D \leq 0.5$ nm

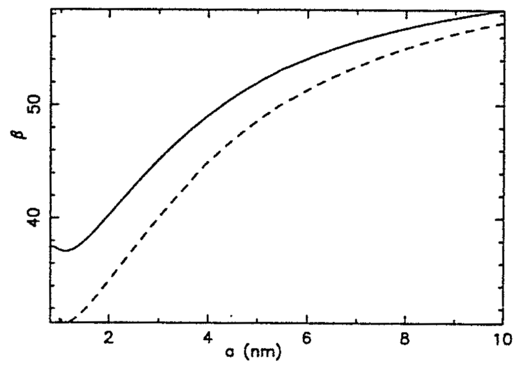
◇ For a (9,0), β is only around 200

⇒ Phenomena other than polarization are probably involved in the emission

Influence of the density



Polarization potential in the XY plane (top) at $Z = 8.5$ nm and XZ plane (bottom) at $Y = 0$ for a rope of 13 (6,0) nanotubes



Evolution of the β factor with the mesh parameter. Solid line $\rightarrow$ first nearest neighbors, dashed line $\rightarrow$ first+second nearest neighbors

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◇ The β factor decreases when the density is increased

$\Rightarrow$ To have a uniform emission $\rightarrow$ decrease the density

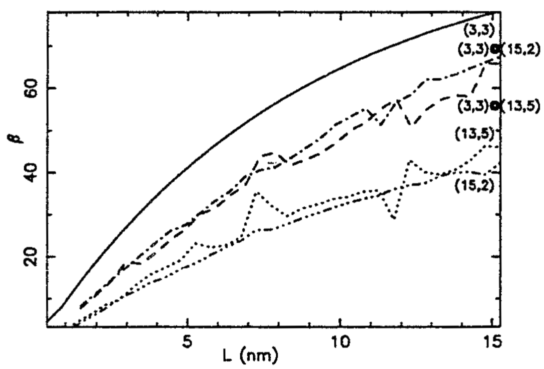
◇ The polarization is larger for the external nanotubes

◇ The X Y components of the field are larger than the Z component

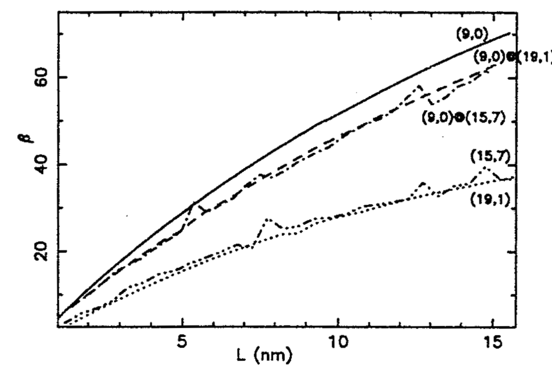
$\Rightarrow$ Emission from the brim of the rope $\rightarrow$ large opening of the beam

Multi wall nanotubes

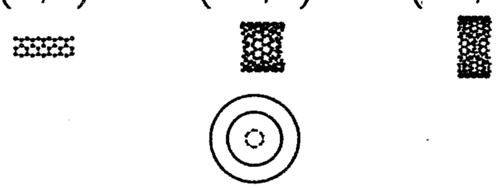
(3,3)@(13,5) and (3,3)@(15,2)



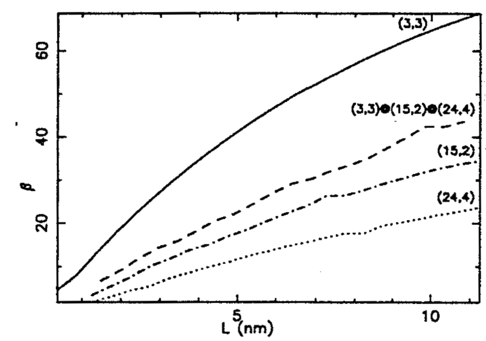
(9,0)@(19,1) and (9,0)@(15,7)



(3,3) (15,2) (24,4)



(3,3)@(15,2)@(24,4)



- ◇ No significant influence of chirality
- ◇ The maximum value of the β factor is given by the inner shell
- ◇ The addition of shells tends to sweep out the instabilities of the β factor
- ◇ The outer shells tend to reduce the enhancement property of the inner shell $\longrightarrow$ Faraday cages

Conclusions

- ⇒ No influence of the band structure on the polarization
- ⇒ Saturation of the polarization with the length of the nanotubes
- ⇒ The saturation sets up faster for (n,n) nanotubes
- ⇒ (n,0) nanotubes are the best field amplifier
- ⇒ The largest β factor observed for isolated SWNT is only of the order of 200 $\rightarrow$ other phenomena are probably involved
- ⇒ In the case of a rope, the induced field is larger close to the brim
- ⇒ The field amplification of MWNT seems to be due to small inner tubes

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