

# POROUS SILICON MULTILAYERS AND MICROCAVITIES

**Prof. Lorenzo Pavesi** (Univ. of Trento)

**Massimo Cazzanelli\*** (Trinity College Dublin)

**Claudio Mazzoleni** (Univ. of Trento)

**Pascal Dubois**

**Roberta Guardini** (Private Company)

**Viviana Mulloni** (Univ. of Trento)

**Rosa Chierchia** (Univ. of Trento)

**Claudio Vinegoni** (Univ. of Pittsburgh)

**\*leaving to University of Geneva**



# OUTLINE

- **introduction**
- **porous silicon**
  - **how to produce it**
  - **structure and morphology**
  - **physical properties**
  
- **dielectric multilayers**
  - **fundamentals**
  - **Bragg reflectors**
  - **Fabry-Perot mirrors**
  - **microcavities**
  
- **porous silicon dielectric multilayers**
  - **characterization**
  - **application to DBR, FPF, PSM**
  - **still open problems**



**Communication technology demands more speed: replacement of electrons with photons as carriers of informations.**

## **PHOTONICS**

**Silicon is the basic material for microelectronics**

### **Indirect-gap semiconductor**

**Low efficiency (1 photon emitted every  $10^7$  electron holes created)**

- increase the efficiency**
- low cost**
- easy integrable**

## **POROUS SILICON**

- emits in the visible**
- 10% external quantum efficiency**

**first aim: produce solid state device**

**LED**





so we obtain a **planar microcavity** with a single allowed photon mode which corresponds to the FP resonance  $\lambda_c$

$\Rightarrow R_{sp}(\eta\omega)$  modified

increased for  $l \approx l_c$

inhibited for  $l \neq l_c$

In order to make PS planar microcavities, dielectric multilayers based on PS are needed

It is necessary to control the thickness and refractive index of a PS layer in a controlled manner.

The **REFRACTIVE INDEX** of PS is determined by its porosity, which depends on the current density of the electro-chemical etching once the other etching parameters are fixed.

The **LAYER WIDTH** is determined by the etching time.

# HOW TO PRODUCE PS

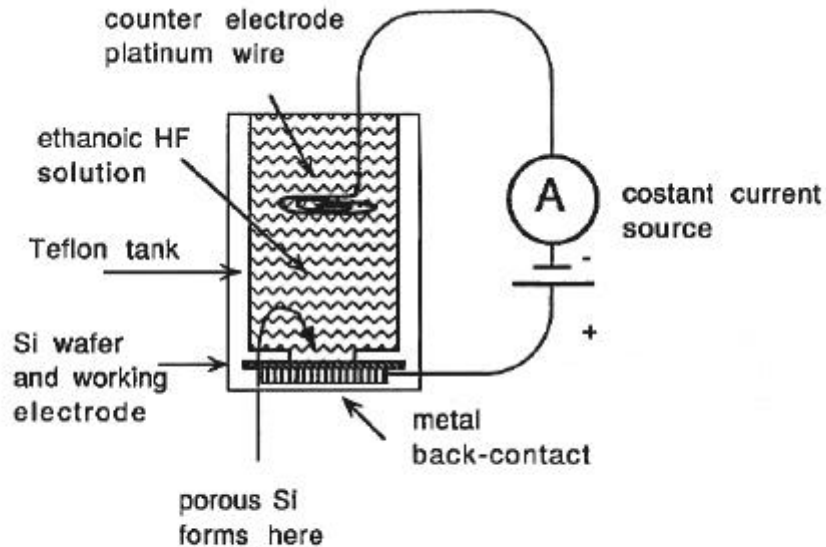


Fig. 4. - Schematic drawing of the electrochemical cell used for the preparation of the porous silicon.

- Si wafer must be anodically biased (forward biasing for p-type doped Si, reverse for n-type)
- in case of n-type light must be supplied
- current densities below a critical value must be used

**HOLE**s regulate the mechanism of formation of PS

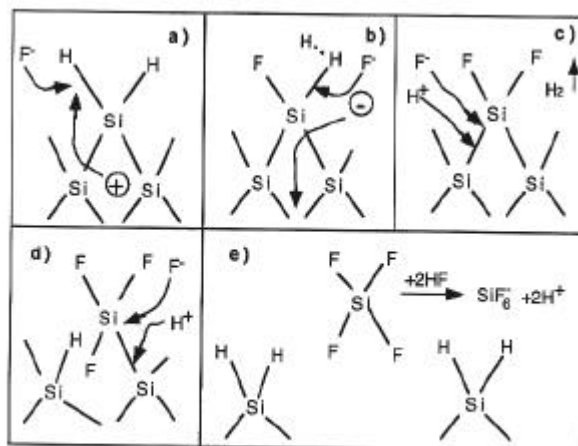
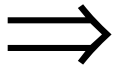
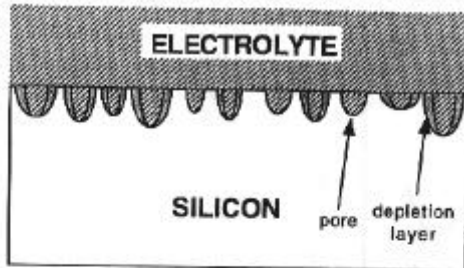


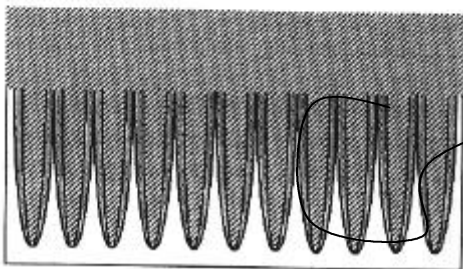
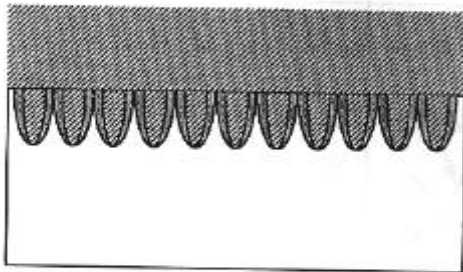
Fig. 1. - Silicon dissolution mechanism proposed by Lehmann and Gosele in ref. [54].



PS formation is a **SELF-REGULATED** mechanism, with hole depletion as the limiting agent



- **unidirectional** (follows the current flow)
- starts at defects on the surface (Si-O)

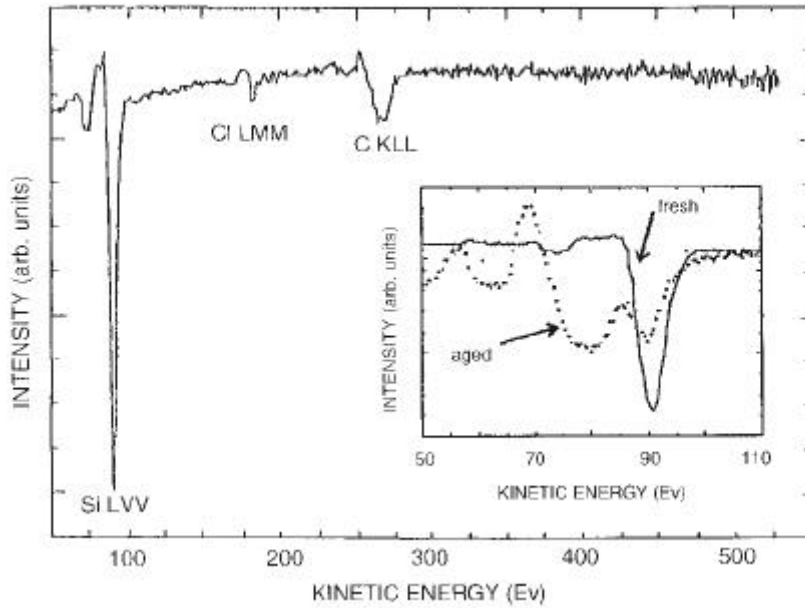


**depletion area**

## **CRITICAL PARAM. FOR PS FORMATION**

- substrate doping
- current density (determines depletion width and carr. Inj.)
- HF (determines current upper limity)
- etching times (chemical + electroch. Dissolution)
- illumination (n-type)
- solvent in wich HF is diluted

# STRUCTURE AND MORPHOLOGY OF PS

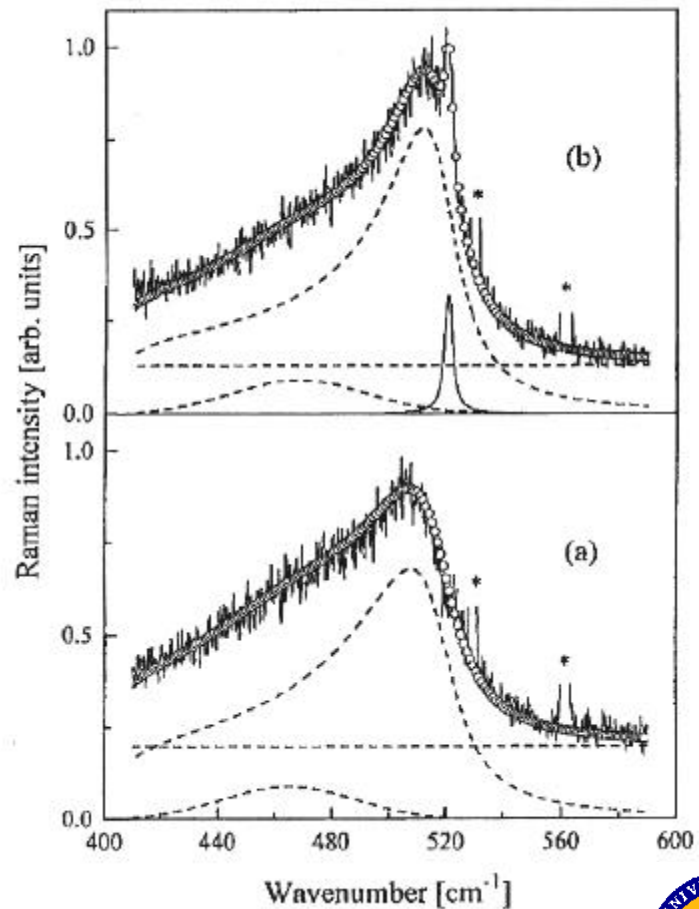


**AES**

**AES** indicates **no presence of O** atoms as in crystalline Si (surface)

**Raman spectr.**

**(phonon confinement)**

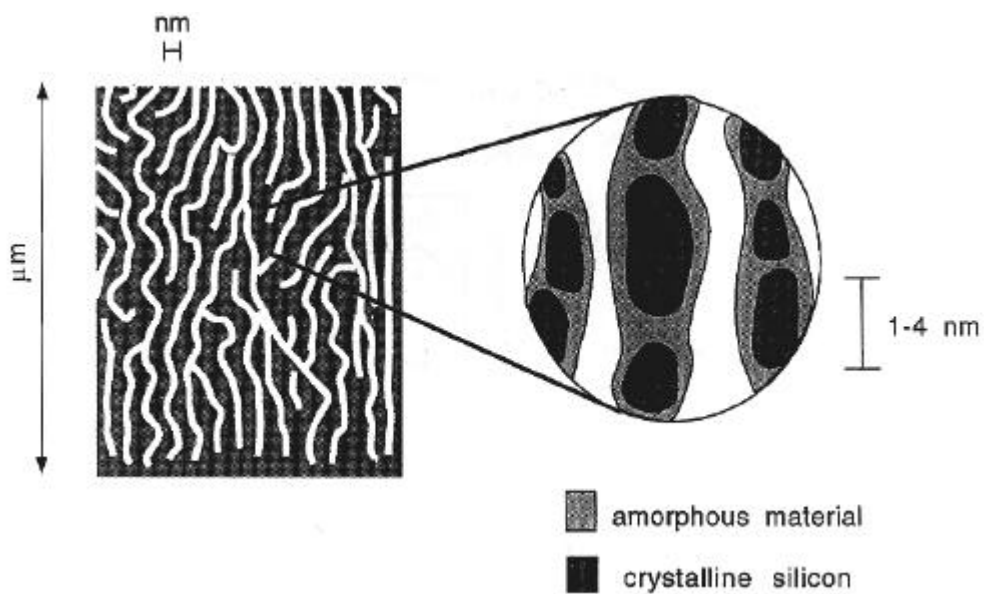


**(b) PS-BULK**

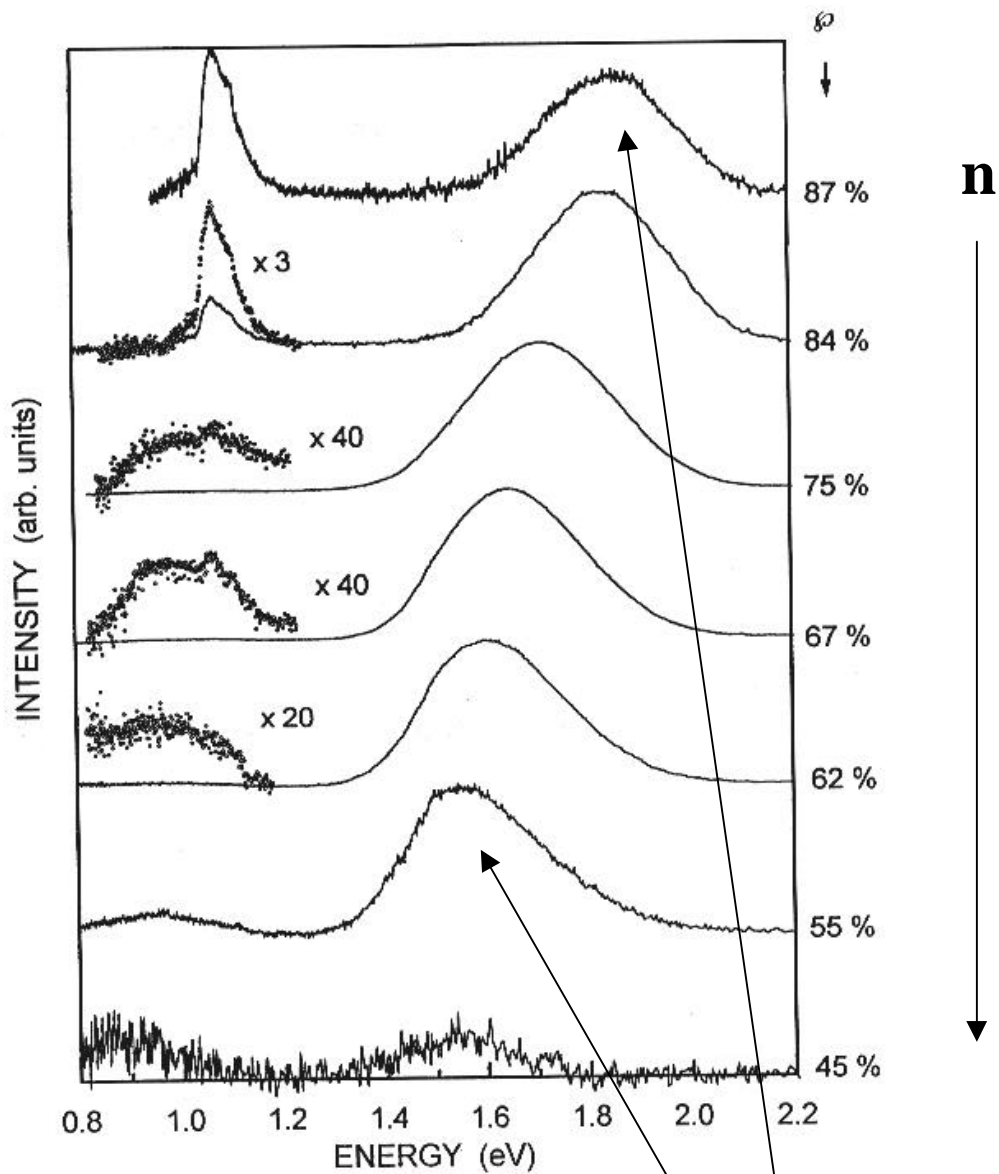
**(a) PS-AIR**

**MODEL:** layer made of voids and nanocrystals interconnected by an amorphous matrix.

aging -> H substituted with O



# PHOTOLUMINESCENCE



- blue band (2.3-2.6 eV)
- VISIBLE BAND (1.4-2.2 eV)
- ir (0.8 eV)

blue shift

## **Canham: QUANTUM MODEL of ps**

**disordered array of quantum wires or dots where the excitons are confined. It follows that excitonic transition energy becomes greater with the decreasing of size (particle in a box model)**

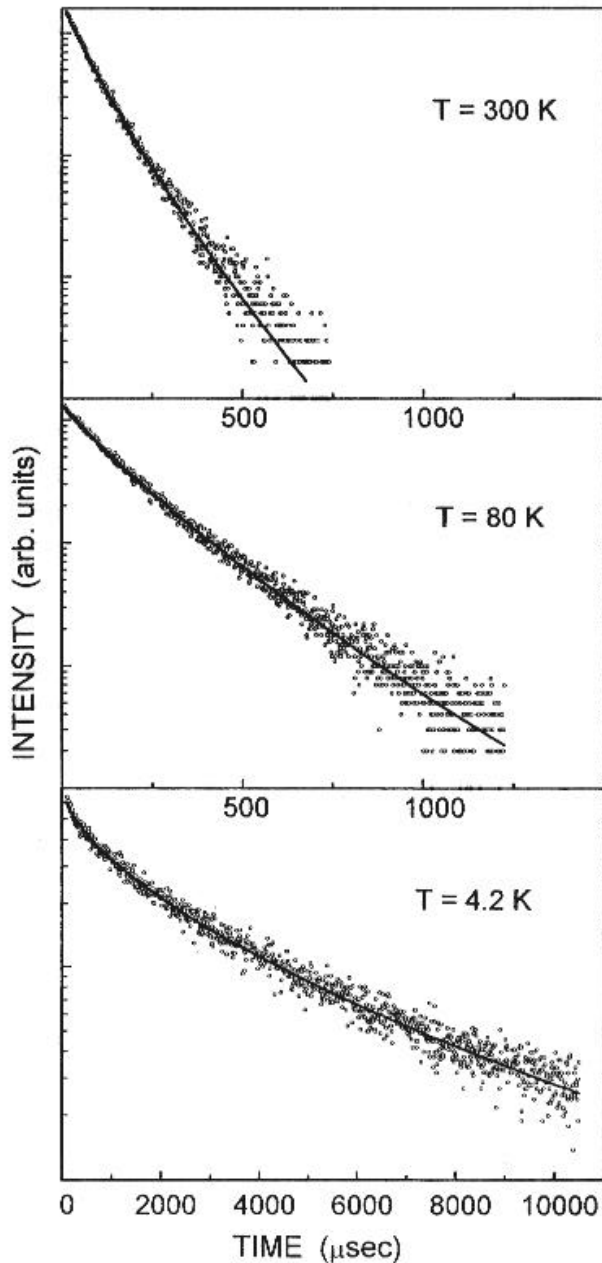
**this is supported from the measurements done (n vs. energy).**

**Width of the band explained by size distribution.**

**From absorption measurements -> exp edge resulting from the overlap of different edges.**



# RECOMBINATION DYNAMICS



$$I_{PL}(T) = I_0 \exp\left(-\frac{t}{\tau}\right)^b$$

**The decay is  
NON EXPONENTIAL**

**(disordered system)  
result from a diffusive motion of  
the excited carriers**

**TRLPL**

# How we explain TRLPL

excitons before recombination move through the nanocrystals skeleton

## RECOMBINATION

- on-site recombination
- exciton diff.

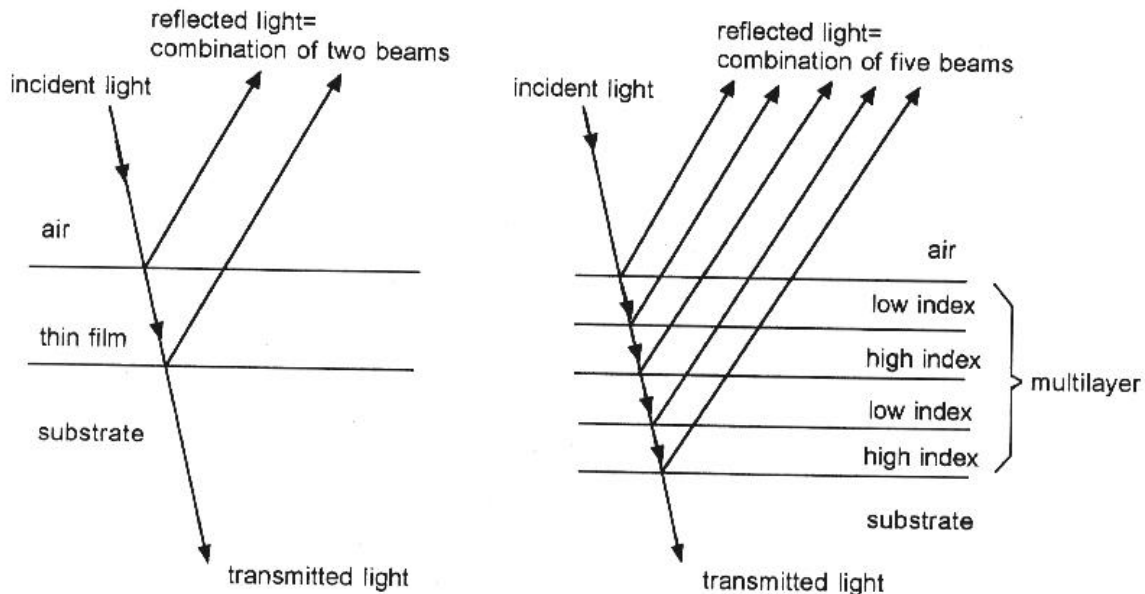
**Exciton diffusion** controlled by:

- hopping time from one crystal to the other
- confining energy of the crystal



# DIELECTRIC MULTILAYERS

## Multiple interferences



Choosing appropriate index of refraction and thickness we obtain constructive and destructive interference at the desired

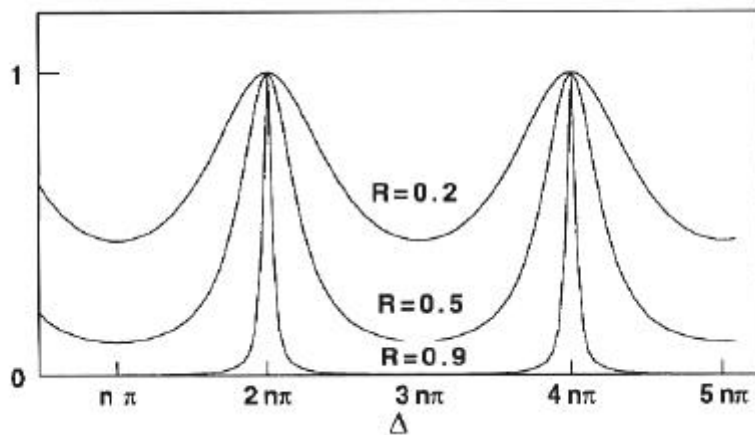
$$I_T = I_0 \frac{T^2}{1 - R^2} \frac{1}{1 + F \sin^2 \frac{\Delta}{2}}$$

**Thin slab**

$$F = \frac{4R}{(1 - R^2)}$$

**Finesse**

(measure of the sharpness of the fringes)



**Airy function**

## **DIELECTRIC BRAGG REFLECTORS**

Mathematical treatment via **transfer matrix approach**, if we have more than one layer.

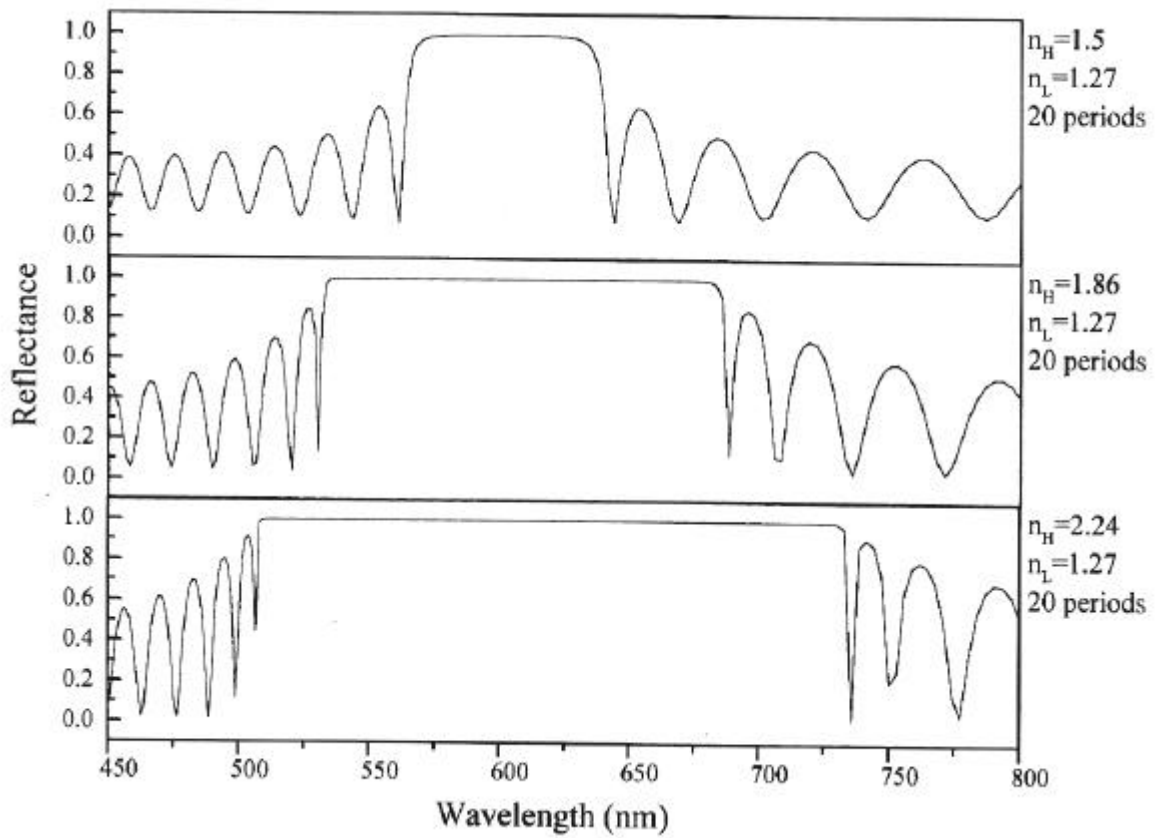
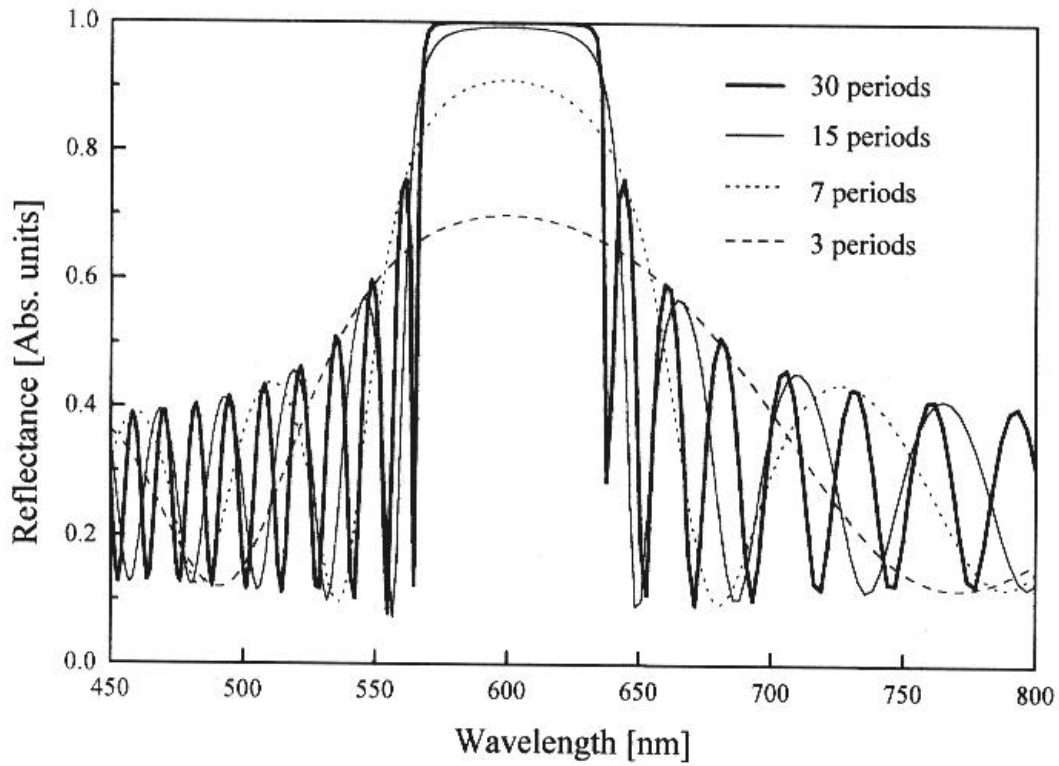
$$R = \left[ \frac{(n_H / n_L)^{2N} - 1}{(n_H / n_L)^{2N} + 1} \right]^2$$

**N fixed:**  $R, n_H/n_L$   
 **$n_H/n_L$  fixed:**  $R, N$

- $n_H$  high refractive index layer
- $n_L$  low refractive index layer
- thickness  $\lambda/4$

Named: **DIELECTRIC BRAGG MIRROR**





## Conclusions:

- increasing  $N$ ,  $R$  increases
- increasing  $N$ , the stop band enlarges
- increasing  $N$ , the stop band sharpens
- increasing  $nH/nL$  the stopband enlarges and sharpens
- increasing  $nH/nL$  the reflectance values increase everyw.



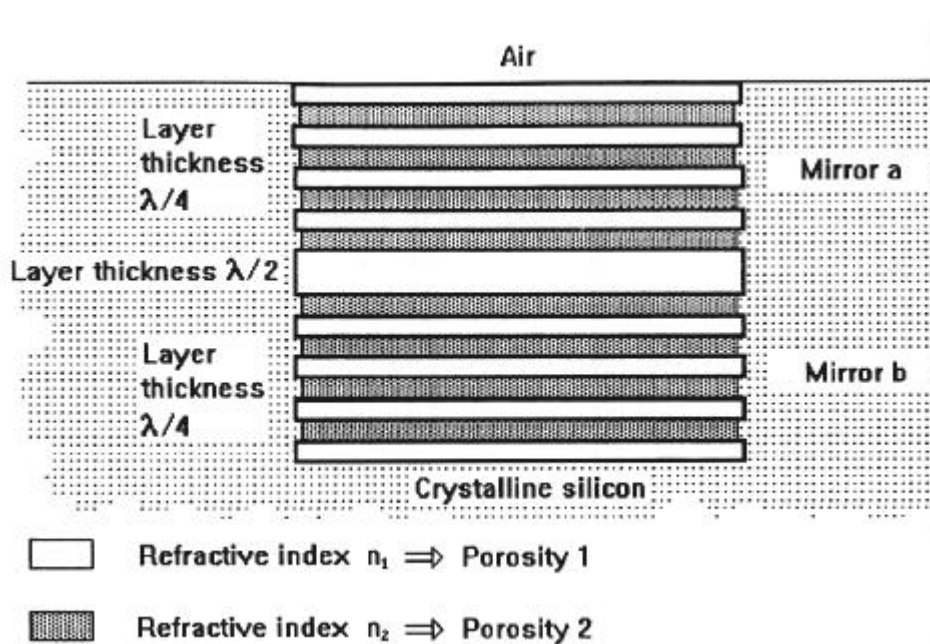
# FABRY PEROT INTERFERENCE FILTERS

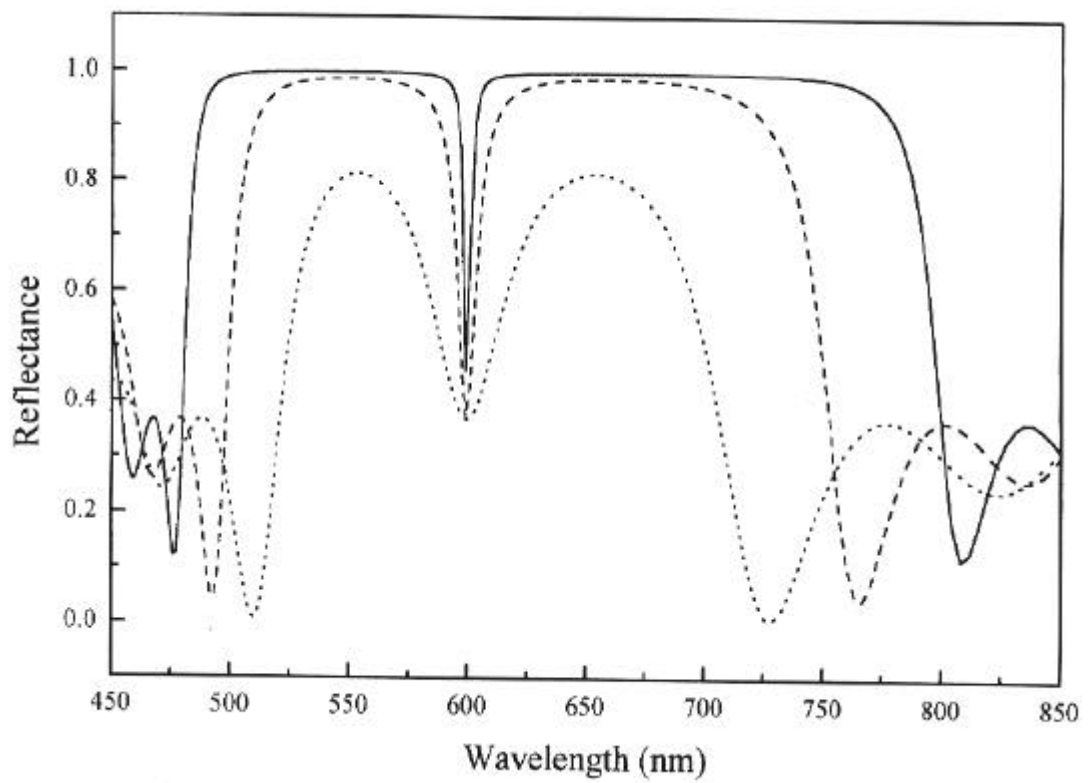
Using two parallel mirrors separated by a spacer it's possible to construct a particular class of interferometer; **Fabry-Perot interference filters**

- **Narrow pass-band**
- **based on multiple reflections of two mirrors**

Particular class of FP filters based on **dielectric multilayers**

**Idea:** use two DBR separated by a spacer formed by the same material but with a different ref. Index and it should be  $\lambda$  or  $\lambda/2$  thick.

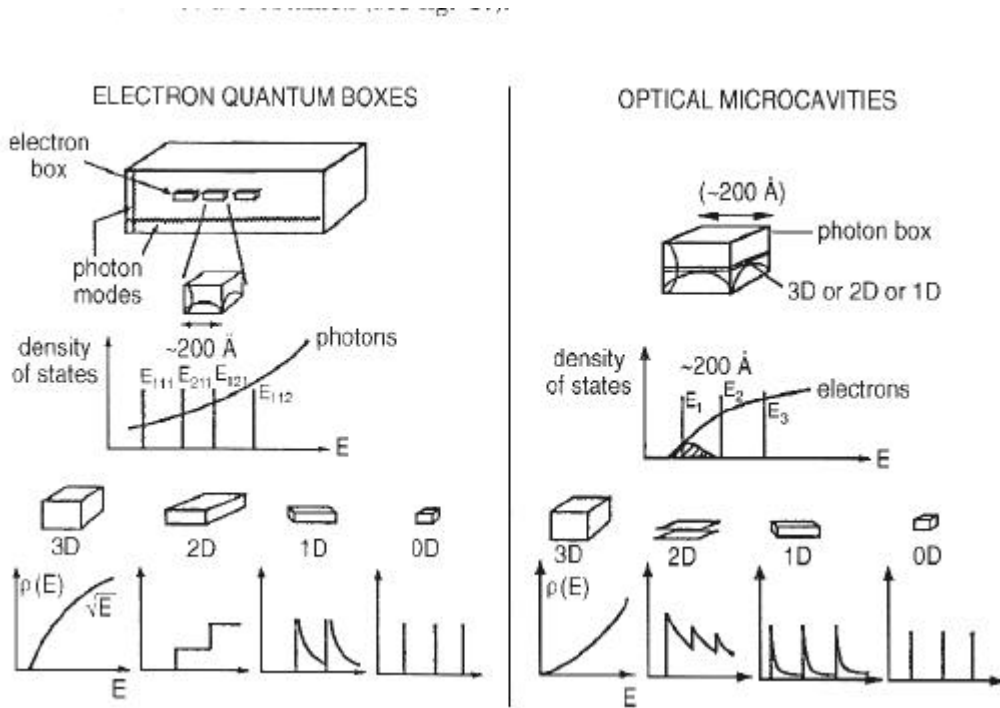




# MICROCAVITIES

Spontaneous emission rate given by the product of the electronic matrix element and the photon mode density

$$R_{sp}(\eta\omega) = \left(\frac{2p}{\eta}\right) \sum_{f,i} |\mathbf{H}_{i,f}|^2 \mathbf{G}(\eta\omega) P_i (1 - P_f) d(E_{fi} - \eta\omega)$$



Light confinement in optical cavity

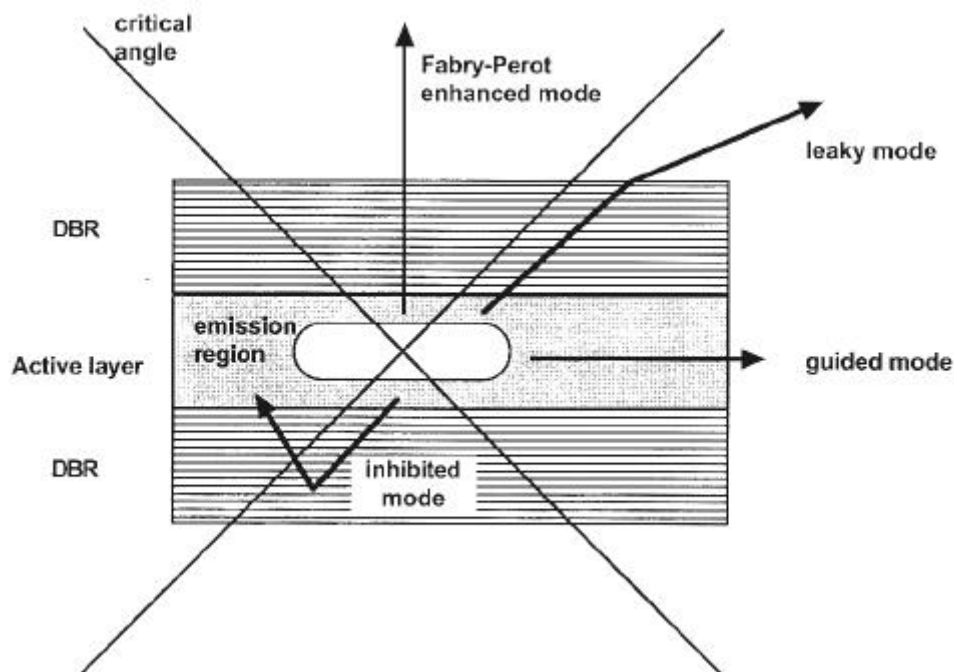
**Imagine two FPR with an active media between them.**

**Multiple in-phase reflections which occur on the mirrors.**

**allowed photon states: transmission permitted**

**forbidden photon states: all light reflected**

**NB all this for light propagating perpendicular to the mirrors**



$$b = \frac{\text{spontaneous emission in the desired mode}}{\text{spontaneous emission in all modes}}$$

# DIELECTRIC PS MULTILAYERS

## Porosity dependence of the refractive index of PS

Maxwell-Garnett approximation (spherical particles):

$$\frac{\mathbf{e}_{eff} - \mathbf{e}_M}{\mathbf{e}_{eff} + 2\mathbf{e}_M} = f \frac{\mathbf{e} - \mathbf{e}_M}{\mathbf{e} + 2\mathbf{e}_M}$$

$\mathbf{e}_M$  embedding environment       $f$  volumetric fraction

$\mathbf{e}_{ef}$  effective index of ref.

$\mathbf{e}$  for silicon

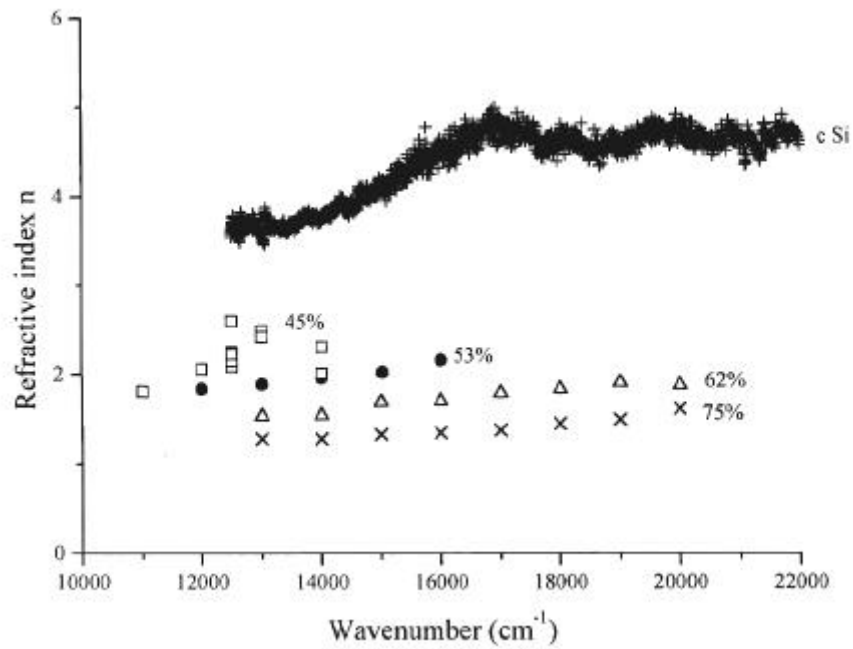
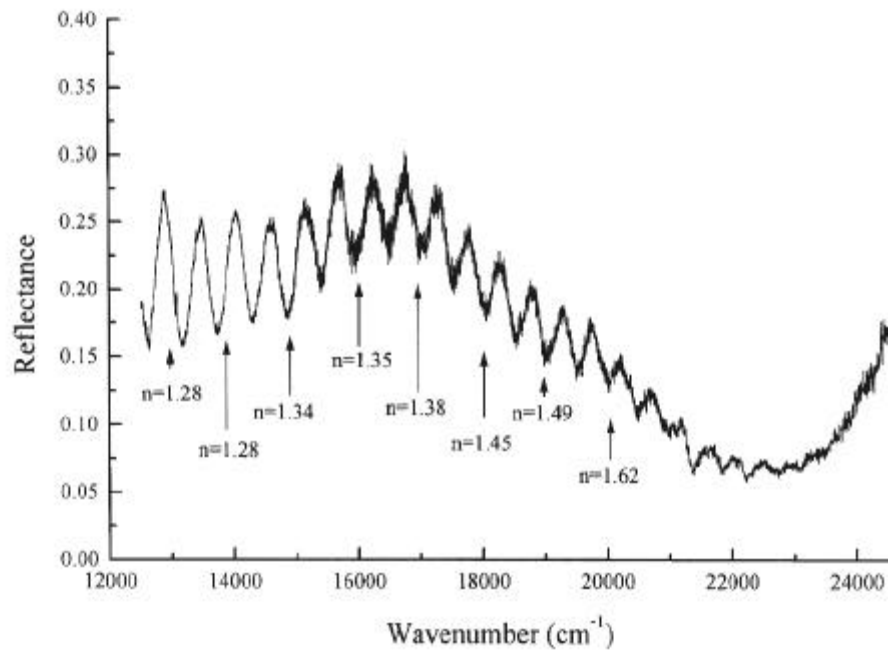
if negligible absorption       $n_{eff}^2 \approx \mathbf{e}_{eff}$   
 $\Rightarrow f$

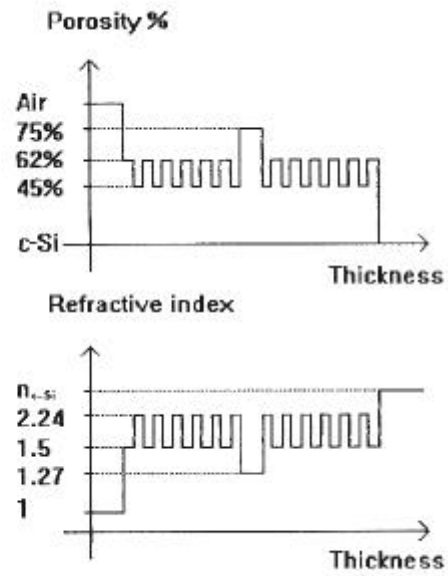
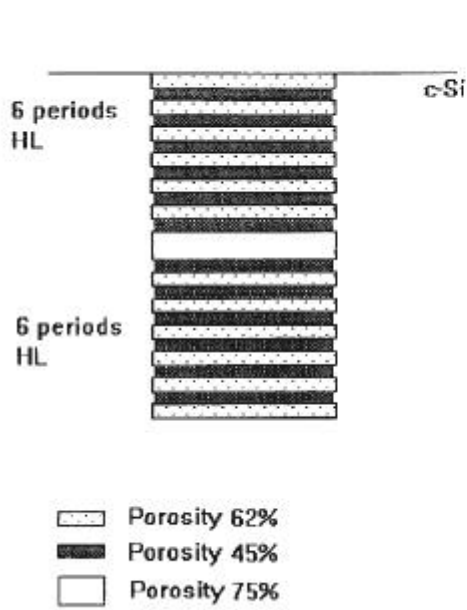
## Determine refractive index

Based on measurements of interference fringes

$$n = \frac{1}{2d} \left( \frac{1}{I_r} - \frac{1}{I_{r+1}} \right)^{-1}$$

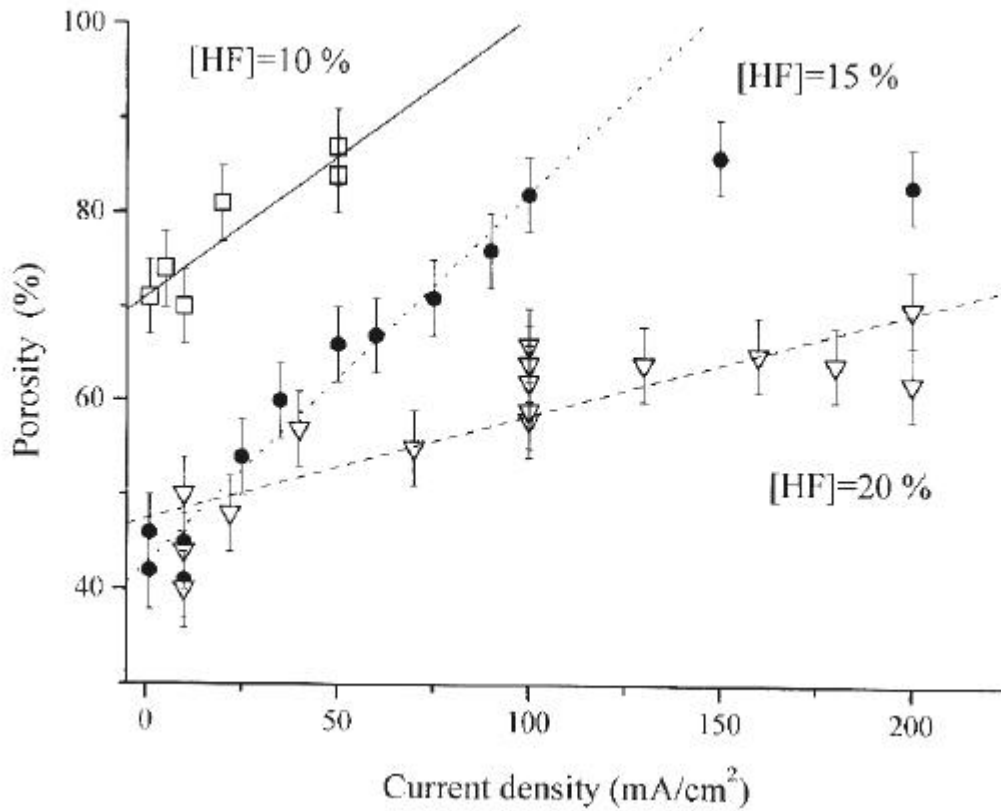


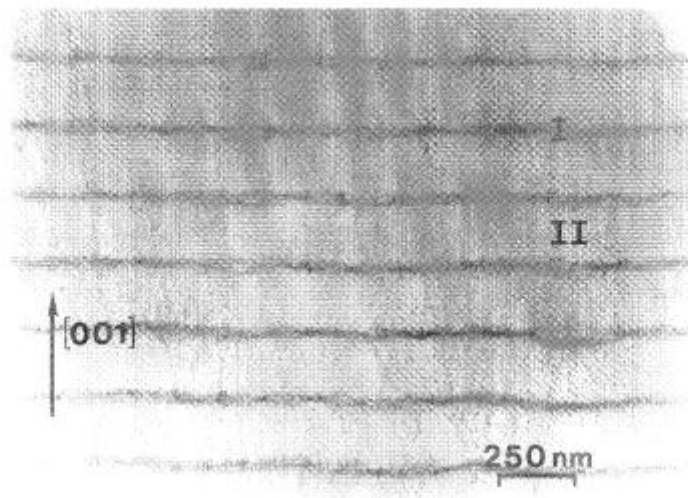
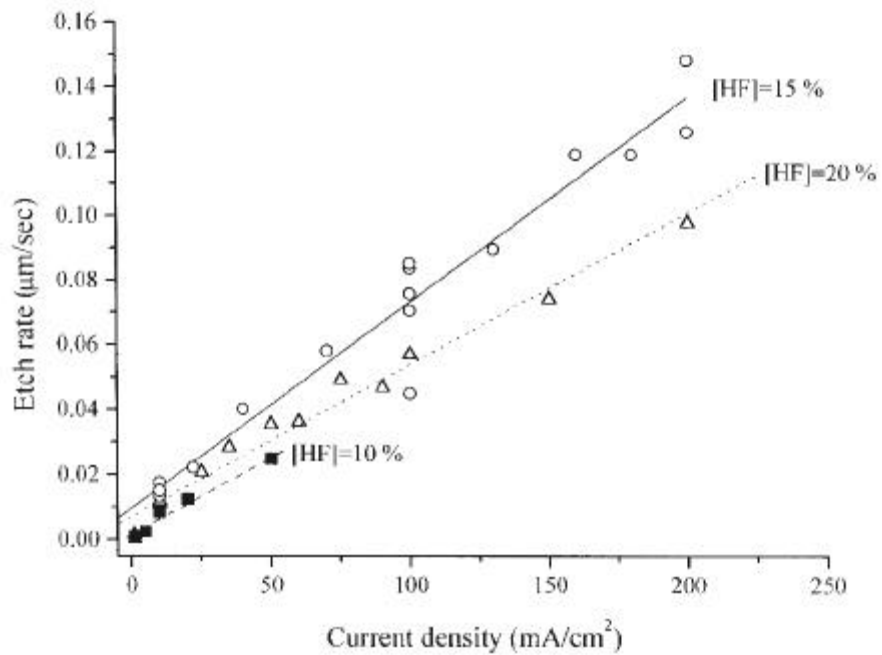




**FP structure**

**porosity/ref.index sequence**



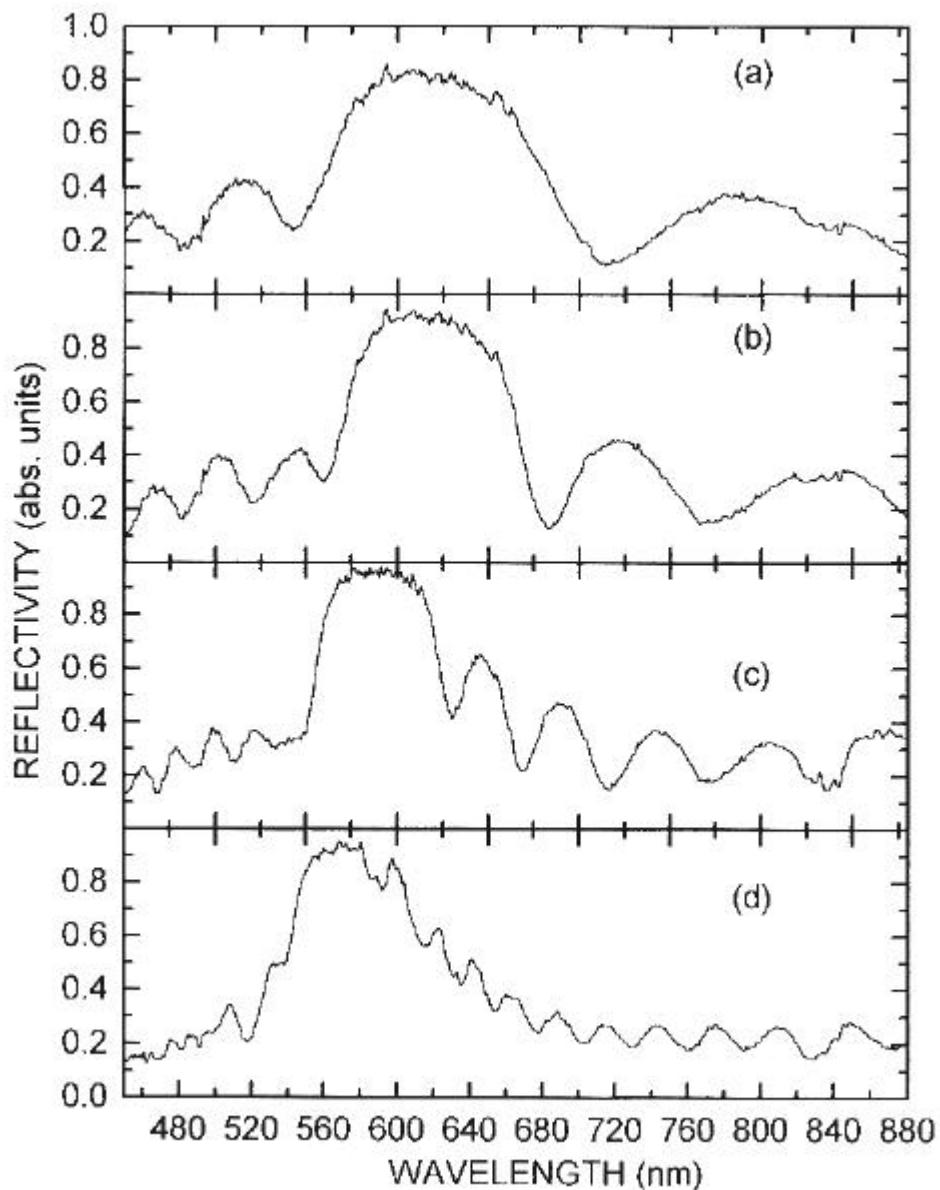


**TEM image**

**layer 1 - 20 nm, 64% porosity**

**layer 2 - 200 nm, 84% porosity**

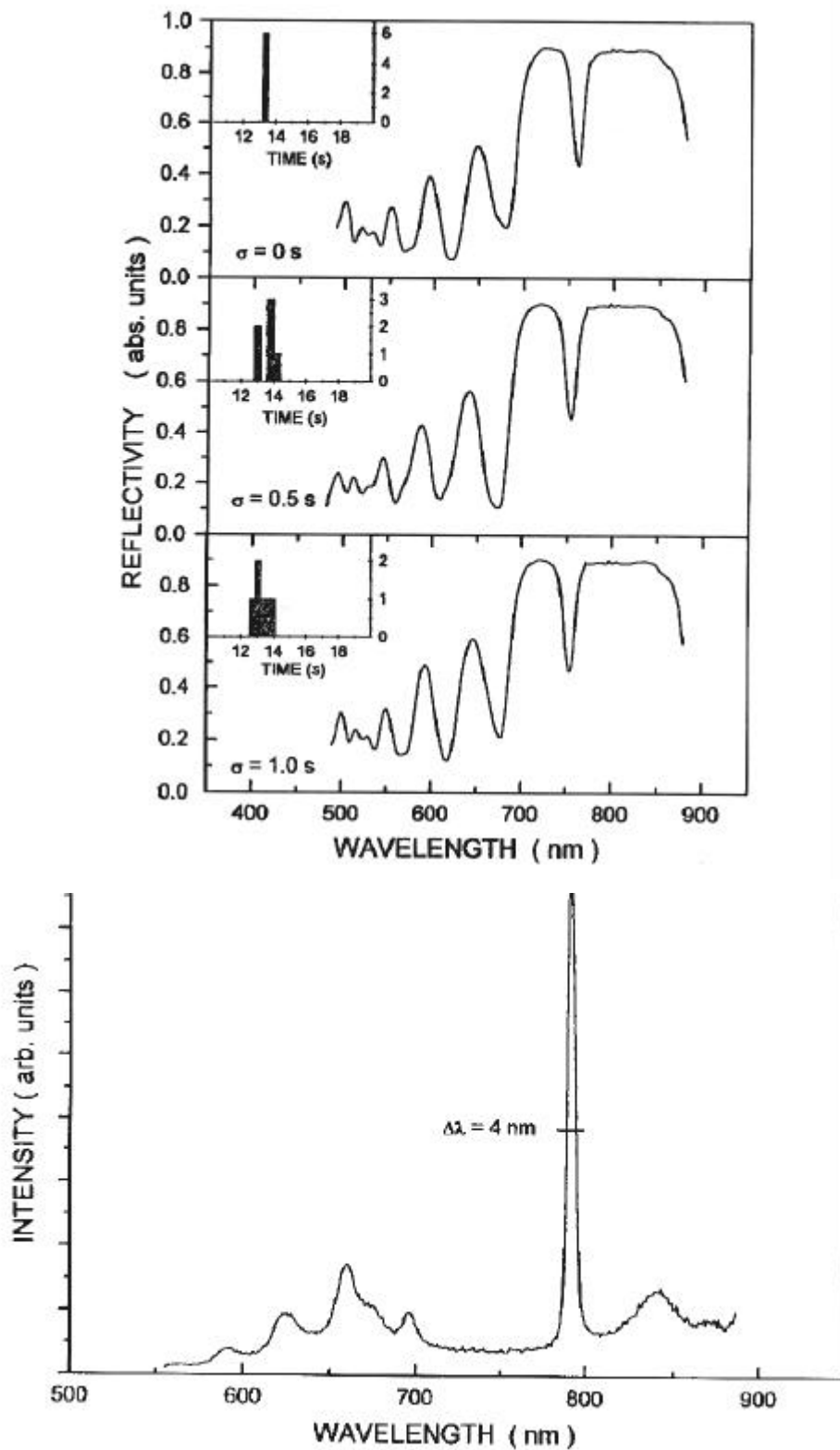
# DIELECTRIC BRAGG REFLECTORS



- (a)** DBR centered at 670 nm 15 rep. of two layers of 62 and 75% porosity
- (b)** DBR centered at 590 nm 15 rep. of two layers of 62 and 75% porosity
- (c)** same as b with 30 rep.
- (d)** DBR centered at 465 nm 15 rep. of two layers of 62 and 75% porosity



# FABRY-PEROT FILTERS (RANDOM)



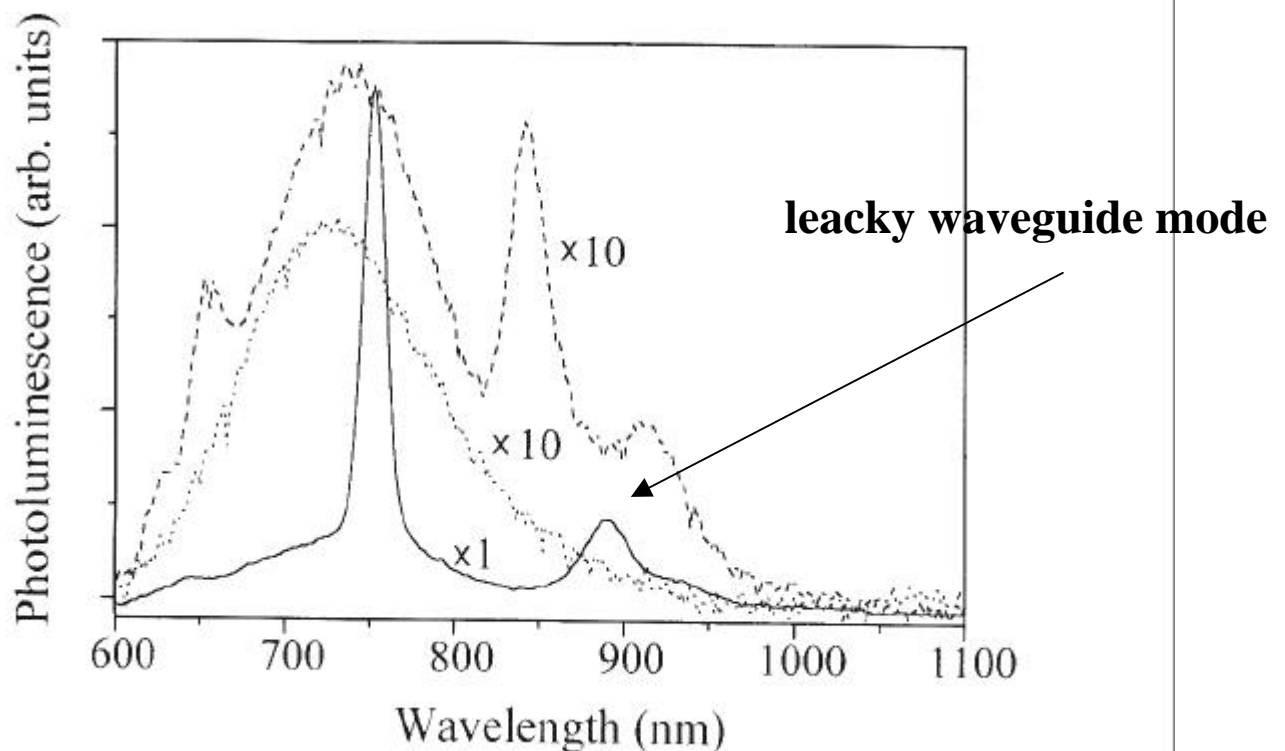
# ALL POROUS SILICON MICROCAVITIES

With a FP we can realize an all-PS microcavity

Top and bottom DBR act as photon **CONFINERS**.

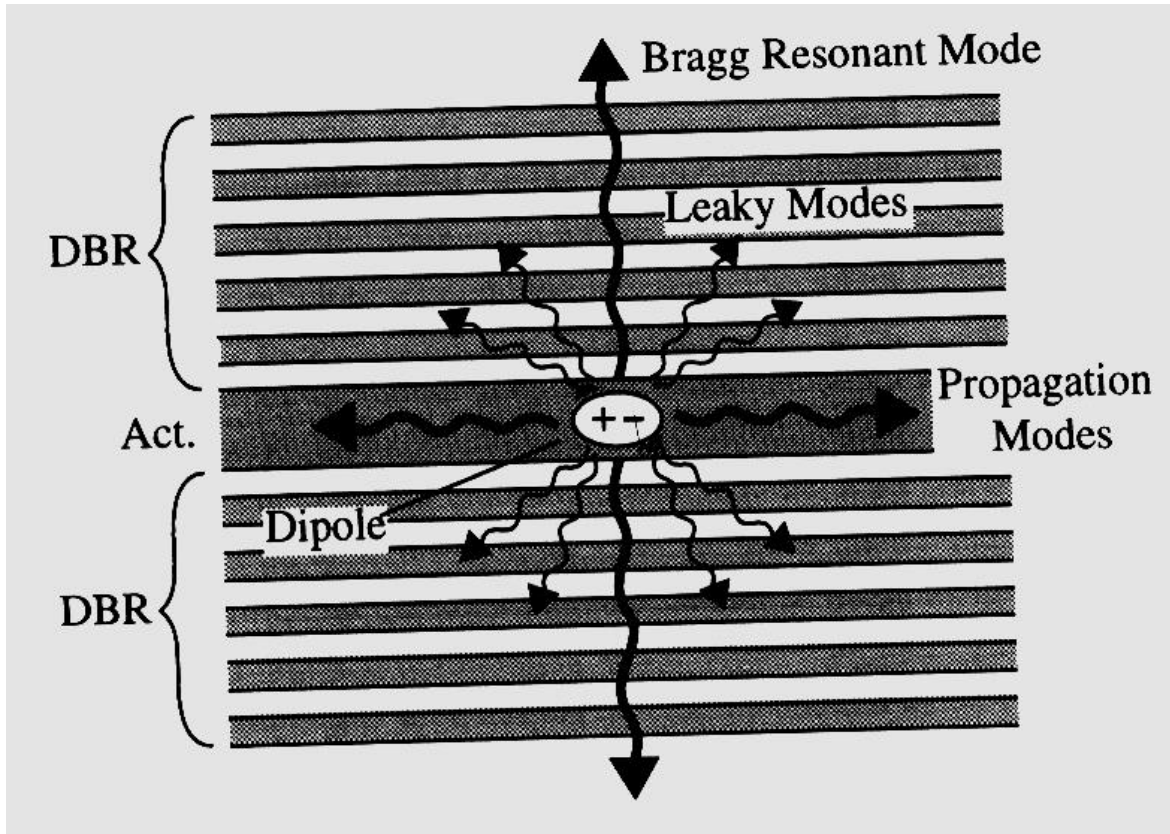
The central layer act as **OPTICALLY ACTIVE MED.**

In the central layer coupling between excitonic transitions and photon modes

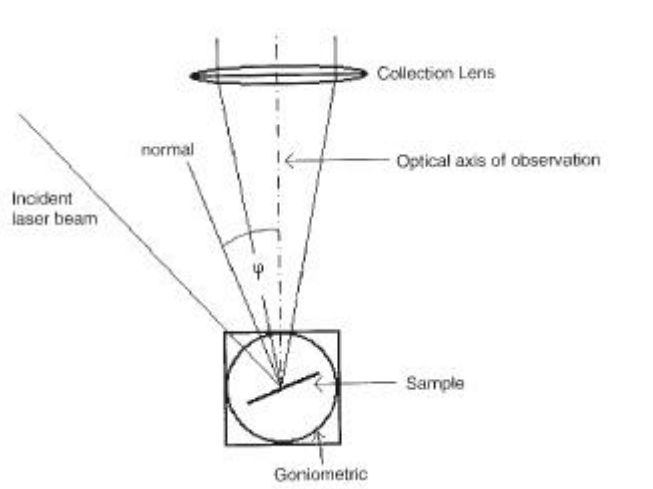


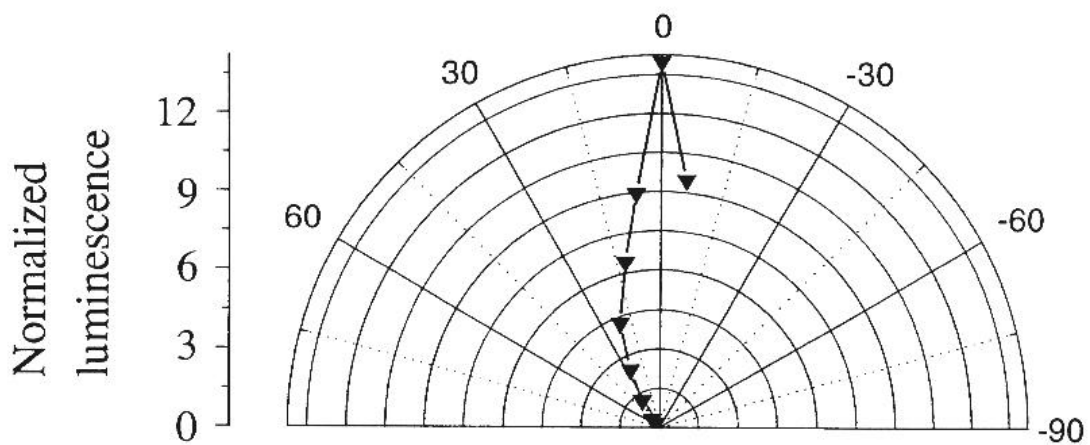
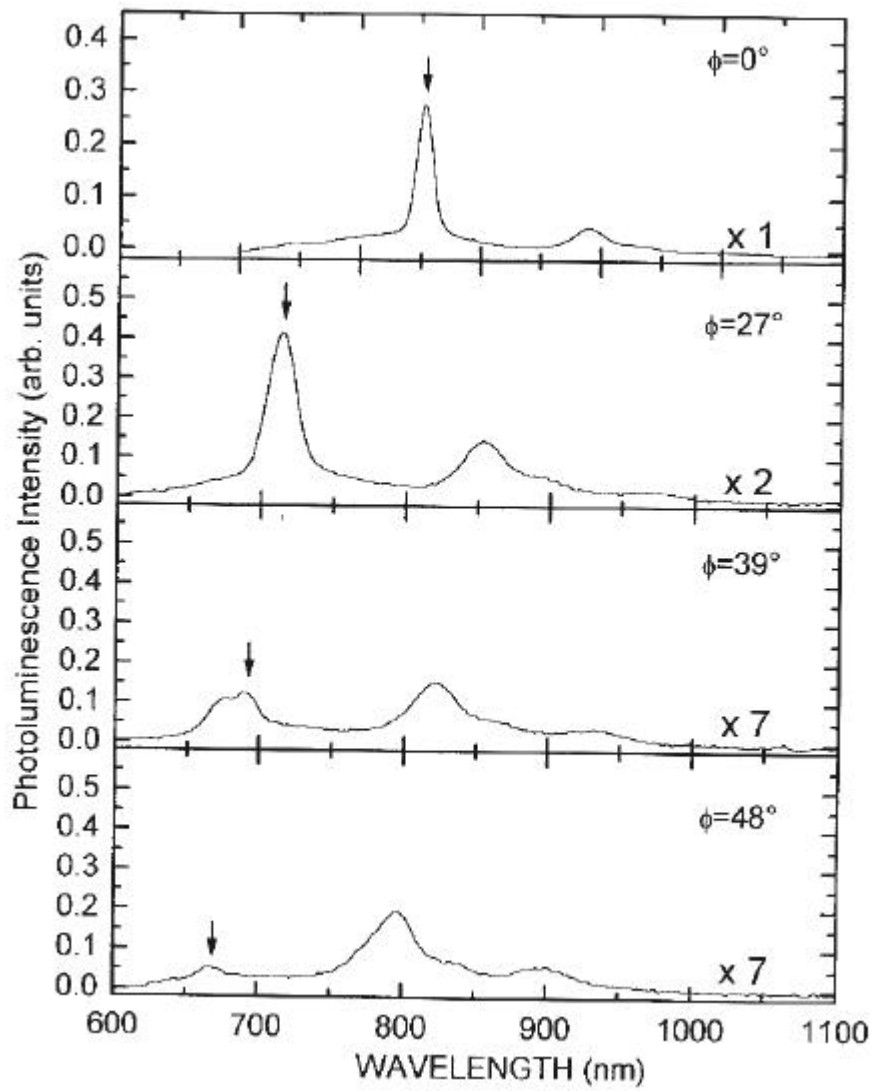
PL spectra of a PSM with resonance at  $\lambda_c$  (solid line)  $\lambda_c$ -thick PS reference layer (dotted line) and of a DBR .

•choosing appropriate width of the active layer and DBR we can tune the wavelength of the PSM taking advantage of the broad emission band of PS



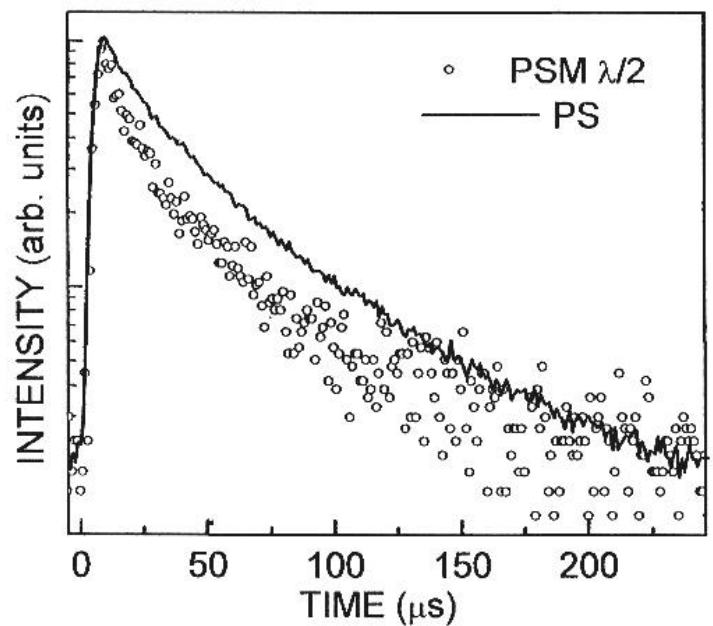
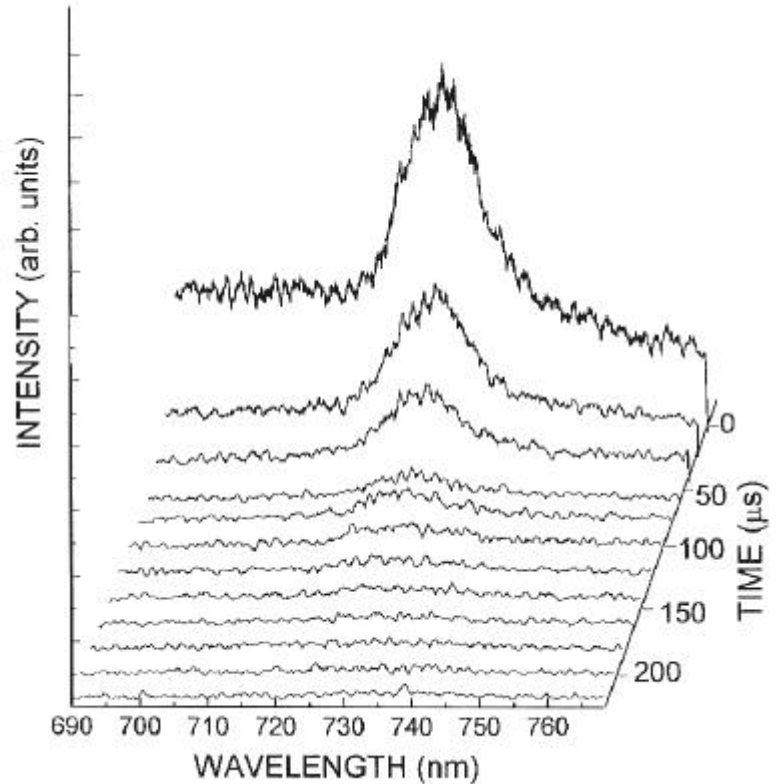
**High angular concentration of output emission**

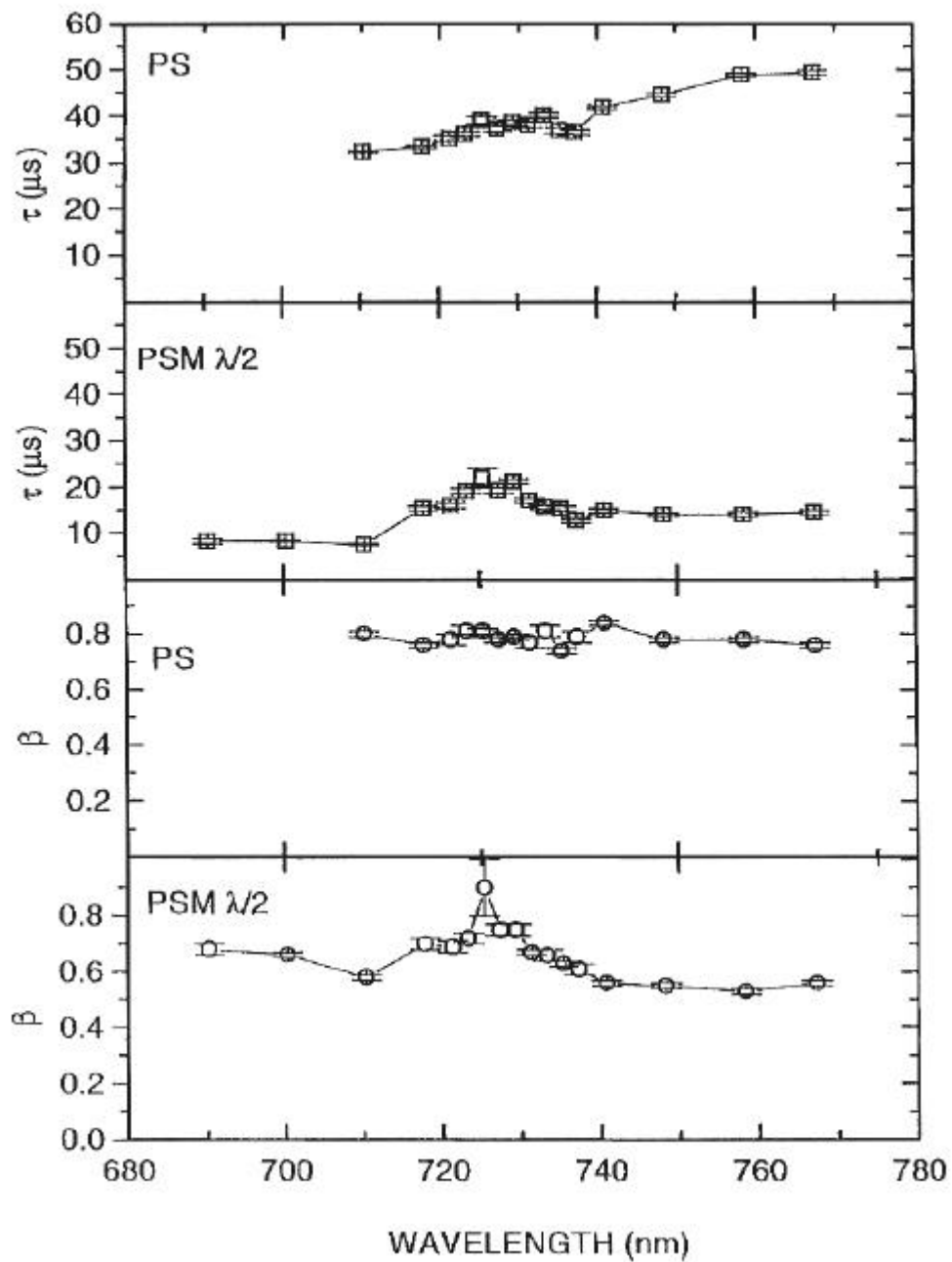




# Time decays of the luminescence in PSM (basic)

- peak at  $\lambda_c=750$  nm doesn't move
- the decay of the side band luminescence is faster than that of the peak at  $\lambda_c$





# CONCLUSIONS

- coupling between photon and exciton mode is weak
- emission takes place in all the central layer
- emission of PS wider than the stop band of DBR
- emission of PS central layer and DBR overlaps

**There is no true photon confinement**

- Finite reflection angle
- photon mode penetrates into DBR

**Theoretical treatment of the coupling of the electronic resonance with the optical mode shows that dielectric microcavities differ from ideal or metallic microcavities.**

**Doesn't modify the spontaneous emission rate but redistribute in space.**

