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SMR.769 - 19

WORKSHOP ON "NON-LINEAR ELECTROMAGNETIC INTERACTIONS IN SEMICONDUCTORS"

1 - 10 AUGUST 1994

"Exitations, responses and backactions in nonlinear photo-excitation processes of low-dimensional semiconductors" Parts I, II & III

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Excitations, responses and backactions in nonlinear photo-excitation processes of low-dimensional semiconductors

Akira Shimizu

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CONTENTS

Part I

Two-Photon Absorption Spectra of Low-Dimensional Excitonic Systems

Akira Shimizu

Institute of Physics, Univ. Tokyo, Komaba, Tokyo, Japan

Coworkers .....

Theory :

T. Ogawa (Osaka City Univ.)

Experiment :

K. Fujii, J. Bergquist, T. Sawada (Canon Res. C.)

H. Sakaki (RCAST, Univ. Tokyo)

R. Cingolani (Univ. Lecce)

M. Lepore, R. Tommasi, I.M. Catalano (Univ. Bari)

H. Lage, D. Heitmann, K. Ploog (Max Plank Inst.)

Fröhlich et al. (1988) Experiment; $\hbar\omega_1 \sim E_g$, $\hbar\omega_2 \sim$ inte subb

Spector (1987) Theory; without exciton effects

Pasquarello & Quatropani (1988) As above

Catalano et al. (1989) Experiment; QW (1)

Tai et al. (1989) As above (1)

Shimizu (1989) Theory; with exciton effects (1)

Theory; electrically biased QW (3)

Pasquarello & Quatropani (1990) Theory; with exciton effe

Fujii et al. (1990) Experiment; electrically biased QW(3

Shimizu, Ogawa & Sakaki (1992) Theory; general formula for d=0, 1, 2, 3 system (1)

Cingolani et al. (1992) Experiment; QWR (2)

Ogawa & Shimizu (1993) Theory; dimensional crossover (2)

---

1. TPA of d = 0, 1, 2, 3 excitons

2. Dimensional crossover

3. TPA of electrically-biased QWS

What is the problem?

One-Photon Absorption

$$\boxed{W_{OPA} = \frac{2\pi}{\hbar} \sum_f |\langle f|V|g\rangle|^2 S_f(\hbar\omega)}$$

where

V : photon-electron interaction

S_f : line-shape function of the final state

Two-Photon Absorption

$$W_{TPA} = \frac{2\pi}{\hbar} \sum_f |\langle f|V^{(2)}|g\rangle|^2 S_f(\hbar\omega_1 + \hbar\omega_2)$$

$$\langle f|V^{(2)}|g\rangle \equiv \sum_\mu \left[\frac{\langle f|V_2|\mu\rangle\langle\mu|V_1|g\rangle}{E_\mu - \hbar\omega_1} + (1 \leftrightarrow 2) \right]$$

where

V_i : V of $\hbar\omega_i$ beam

- What form should be employed for V?

- How to perform the summation over intermediate states?

TPA near half the direct-allowed gap

- For $\hbar\omega_1 \simeq \hbar\omega_2 \simeq E_G/2$,

$$E_\mu - \hbar\omega_1 > E_G/2$$

Hence,

$$\begin{aligned}
\langle f|V^{(2)}|g\rangle &= \sum_\mu \left[\frac{\langle f|V_2|\mu\rangle\langle\mu|V_1|g\rangle}{E_\mu - \hbar\omega_1} + (1 \leftrightarrow 2)\right] \\
&\simeq \frac{2}{E_G} \sum_\mu \left[\langle f|V_2|\mu\rangle\langle\mu|V_1|g\rangle + (1 \leftrightarrow 2)\right] \\
&= \frac{2}{E_G} \left[\langle f|V_2V_1|g\rangle + (1 \leftrightarrow 2)\right]
\end{aligned}$$

$\sum_\mu |\mu\rangle\langle\mu| = 1$

Valid when $E_G \gg$ exciton binding energy

$$\boxed{W_{TPA} \simeq \frac{8\pi}{\hbar E_G^2} \sum_f |\langle f|V_2V_1|g\rangle + (1 \leftrightarrow 2)|^2 \times S_f(\hbar\omega_1 + \hbar\omega_2)}$$

Needs no information on intermediate states!

→ We can take a realistic model!
Can treat excitonic effects, both discrete and continuum states.
Can treat dimensional crossover, etc.

Restriction : $\hbar\omega_1 \sim \hbar\omega_2 \sim E_G/2$

$d = 0, 1, 2, 3$

A Quasi-d-Dimensional Semiconductor

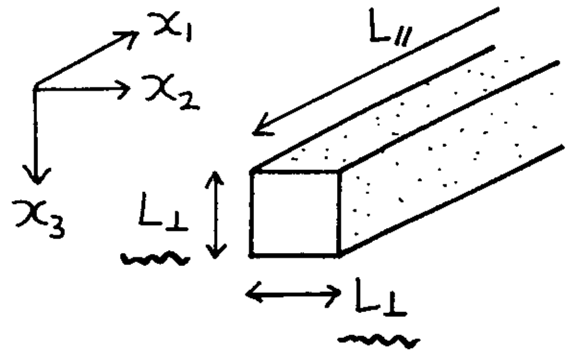
$=$ a QdD well region surrounded by barrier regions

x_ξ $(\xi = 1, \cdots, d)$: unconfined directions

$L_\|$: a normalization length

x_ζ $(\zeta = d+1, \cdots, 3)$: confined directions

$L_\perp$: the well width



A Quasi-d-Dimensional (QdD) Exciton of Wannier type

Assumption

$$\boxed{\text{Lattice constant} < L_\perp < \text{Exciton Bohr radius}}$$

Envelope function

$$\Phi_\nu^{\alpha\beta} = U_\nu^{\alpha\beta}(\vec{r}_{e\|} - \vec{r}_{h\|})\, \phi_\alpha(\vec{r}_{e\perp})\, \phi_\beta^*(\vec{r}_{h\perp})$$

β-th v-subband envelope function

α-th c-subband envelope function

d-D relative motion in the unconfined plane

(For high barriers, $\phi_{\alpha,\beta}(\vec{r}_\perp) \simeq \prod_\zeta \phi_{\alpha_\zeta,\beta_\zeta}(x_\zeta)$.)

$\Psi^{\alpha\beta}(\mathbf{r}_e, \mathbf{r}_h) = \frac{v_0}{\ } \sum \Phi_\nu^{\alpha\beta}(\mathbf{R}_i, \mathbf{R}_i)\, w_c(\mathbf{r}_e - \mathbf{R}_i)\, w_v^*(\mathbf{r}_h - \mathbf{R}_i)$

One-Photon-Absorption (OPA) Spectra

$$W^{(d)}_{\mathrm{OPA}} = \frac{4\pi e^2 |A|^2}{\hbar m_0^2 c^2} \sum_{v=hh,lh} b_v^{(d)} g_v^{(d)}$$

Band part : $b_v^{(d)} = |(c|\hat{\epsilon}\cdot\vec{p}|v)_\perp|^2$

Envelope part: $g_v^{(d)} = (L_\perp + L_B)^{d-3} \sum_{\alpha\beta} |\langle\phi_\alpha|\phi_\beta\rangle|^2$

$$\times \sum_{\nu} |U_\nu^{\alpha\beta}(\vec{r}_\parallel = 0)|^2 \, S_\nu^{\alpha\beta}(\hbar\omega)$$

$\hat{\epsilon}$: polarization vector

$\hbar\omega$: photon energy

A : vector-potential amplitude

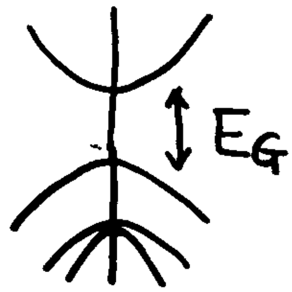
$S_\nu^{\alpha\beta}$: lineshape function of the $\alpha\beta\nu$ exciton

$(c|\hat{\epsilon}\cdot\vec{p}|v)_\perp$: interband matrix element

when $\vec{k} \to 0$ along the confinement directions.

$\hat{\epsilon}$ dependence arises **only** from $(c|\hat{\epsilon}\cdot\vec{p}|v)_\perp$!

One-photon-allowed gap at the Γ point



Nondegenerate case:

The band parameters are

(i) isotropic (if they are isotropic for $d = 3$.)

(ii) d independent

→ Isotropic OPA spectra.

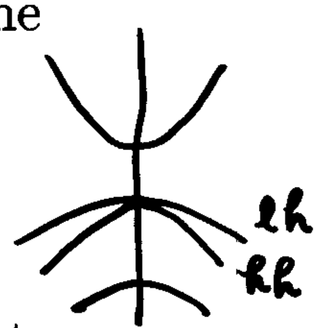
Degenerate case: GaAs, AlGaAs, etc.

Low-dimensional confinement lifts the degeneracy, so that the valance band parameters become

(i) anisotropic

(ii) d dependent

⟶ Anisotropic, d-dependent OPA spectra.



However, even in the absence of confinement, anisotropic perturbations induce similar anisotropic spectra! (G.E.W. Bauer and H. Sakaki, 1992)

$\boxed{\text{Anisotropic OPA spectra} \neq \text{Low-D confinement}}$

OPA spectroscopy is a poor probe of dimensionality

TPA spectroscopy is a sensitive probe of dimensionality

The General Formula for the TPA Rate

$$W^{(d)}_{\mathbf{TPA}}(\hat{\epsilon}) = \frac{64\pi\hbar e^4 |A_1 A_2|^2}{m_0^2 c^4 E_G^2} \sum_{v=hh,lh} \overset{\text{Band part}}{B_v^{(d)}} \underset{\text{Envelope part}}{G_v^{(d)}}$$

(a) When $\hat{\epsilon} \parallel \hat{x}_\xi$ (an unconfined direction),

$$B_v^{(d)} = \frac{|(c|p_\xi|v)_\perp|^2}{\mu_{v\parallel}^2}$$

$$G_v^{(d)} \equiv (L_\perp + L_B)^{d-3} \sum_{\alpha\beta} \underline{|\langle\phi_\alpha|\phi_\beta\rangle|^2}$$

$$\times \sum_\nu \underline{\left| \frac{\partial}{\partial x_\xi} U_\nu^{\alpha\beta}(\vec{r}_\parallel) \right|^2_{\vec{r}_\parallel=0}} S_\nu^{\alpha\beta}(\hbar\omega_1 + \hbar\omega_2).$$

(b) When $\hat{\epsilon} \parallel \hat{x}_\zeta$ (a confined direction),

$$B_v^{(d)} = \frac{|(c|p_\zeta|v)_\perp|^2}{\mu_{v\perp}^2}$$

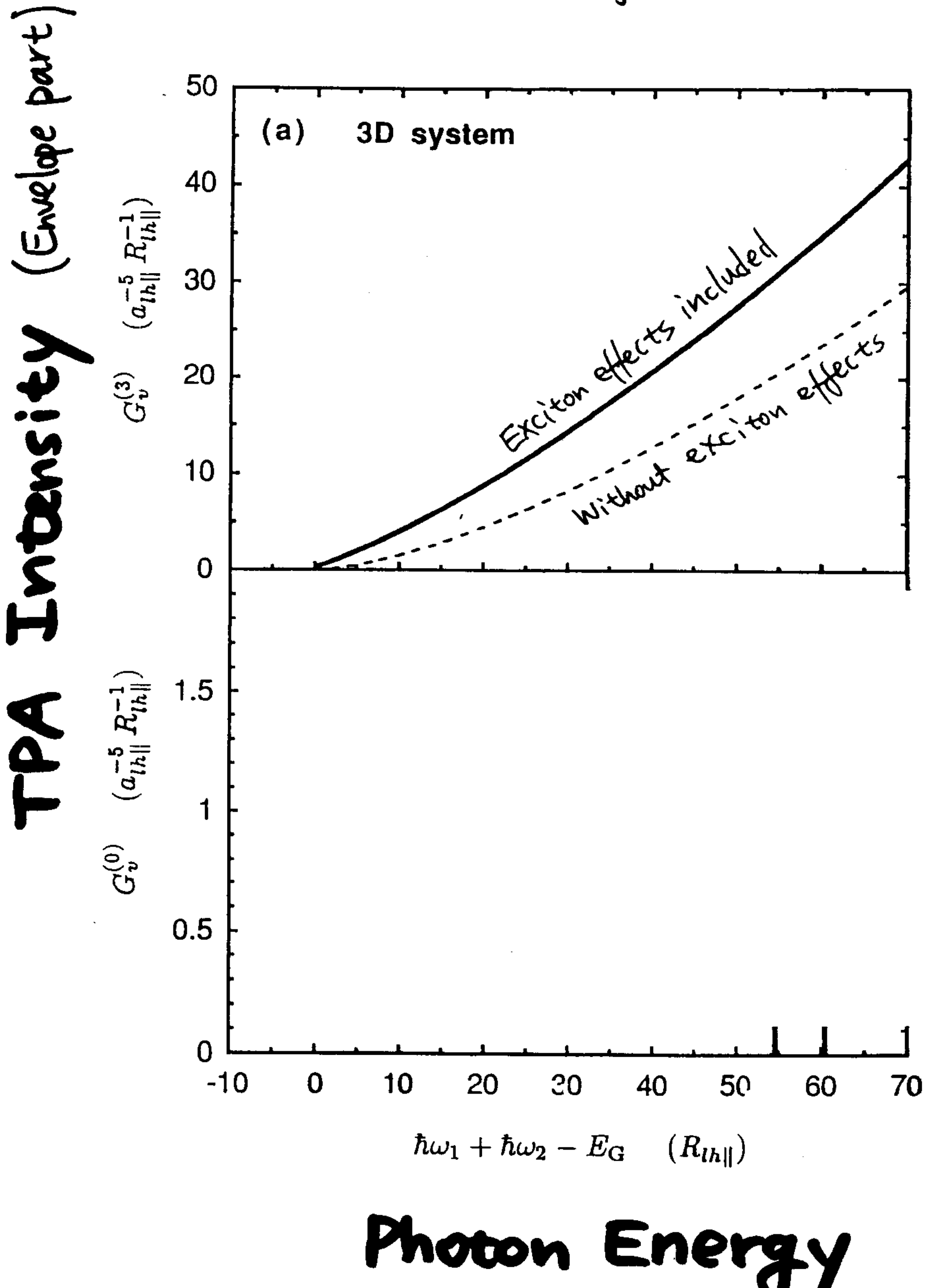
$$G_v^{(d)} \equiv (L_\perp + L_B)^{d-3} \sum_{\alpha\beta} \underline{|\langle\phi_\alpha|\frac{\partial}{\partial x_\zeta}|\phi_\beta\rangle|^2}$$

$$\times \sum_\nu \underline{|U_\nu^{\alpha\beta}(\vec{r}_\parallel = 0)|^2} S_\nu^{\alpha\beta}(\hbar\omega_1 + \hbar\omega_2).$$

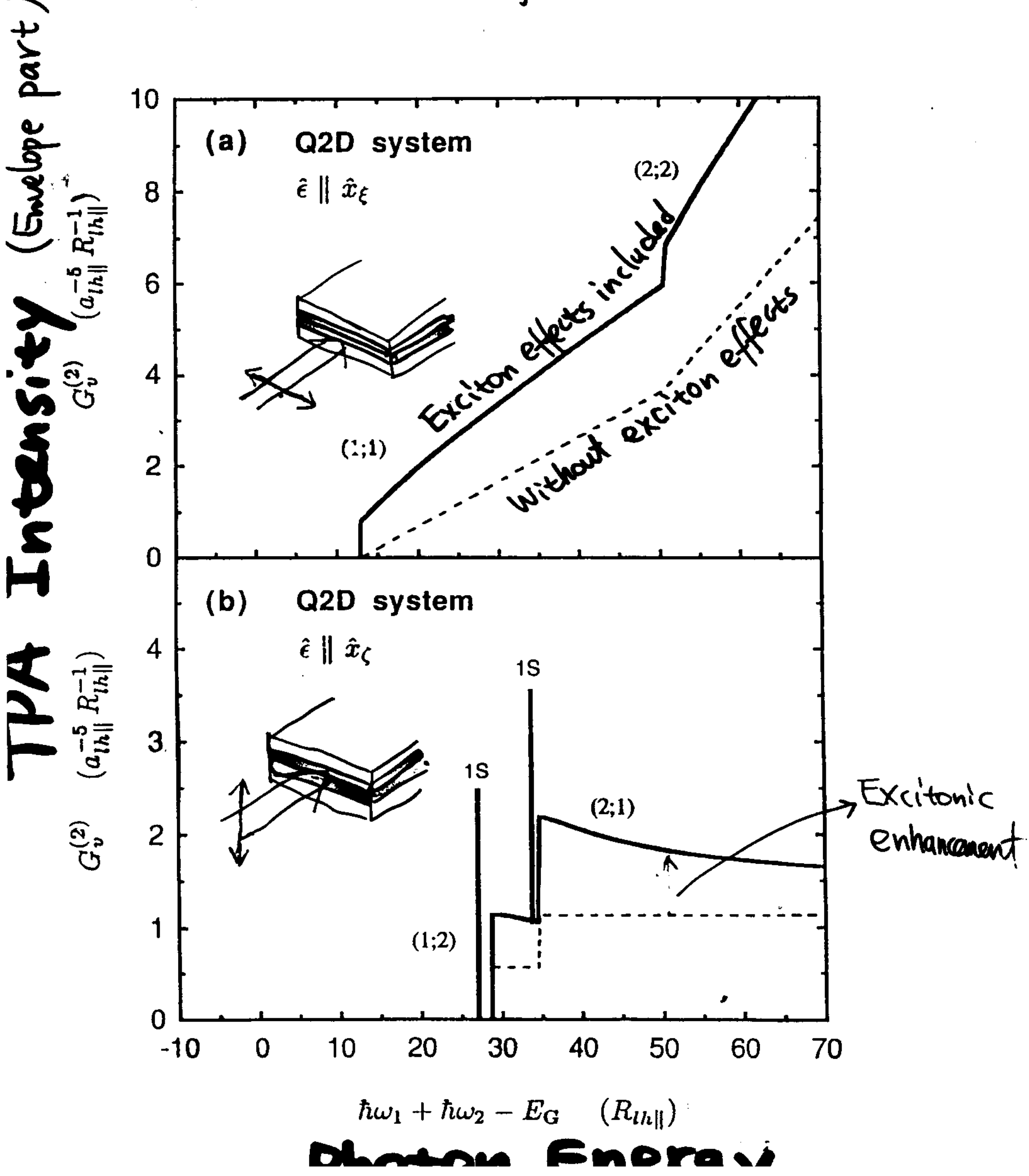
Strong anisotropies from the envelope part!
$\longrightarrow$ Direct evidence of the confinement

Low-D confinement $\equiv$ Low-D envelope function

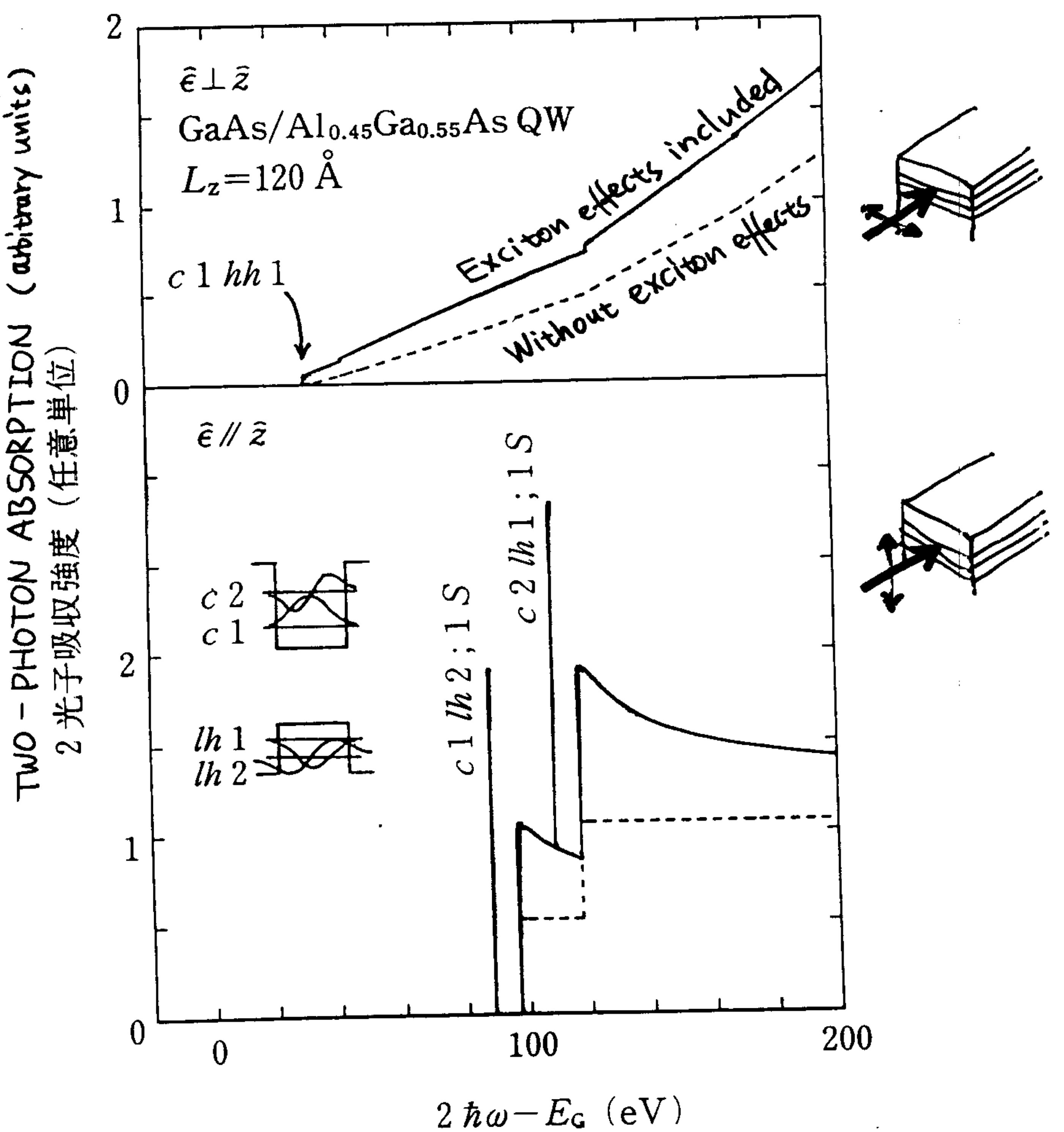
Γ = 10meV is assumed for all discrete level



Γ = 10 meV is assumed for all discrete levels.

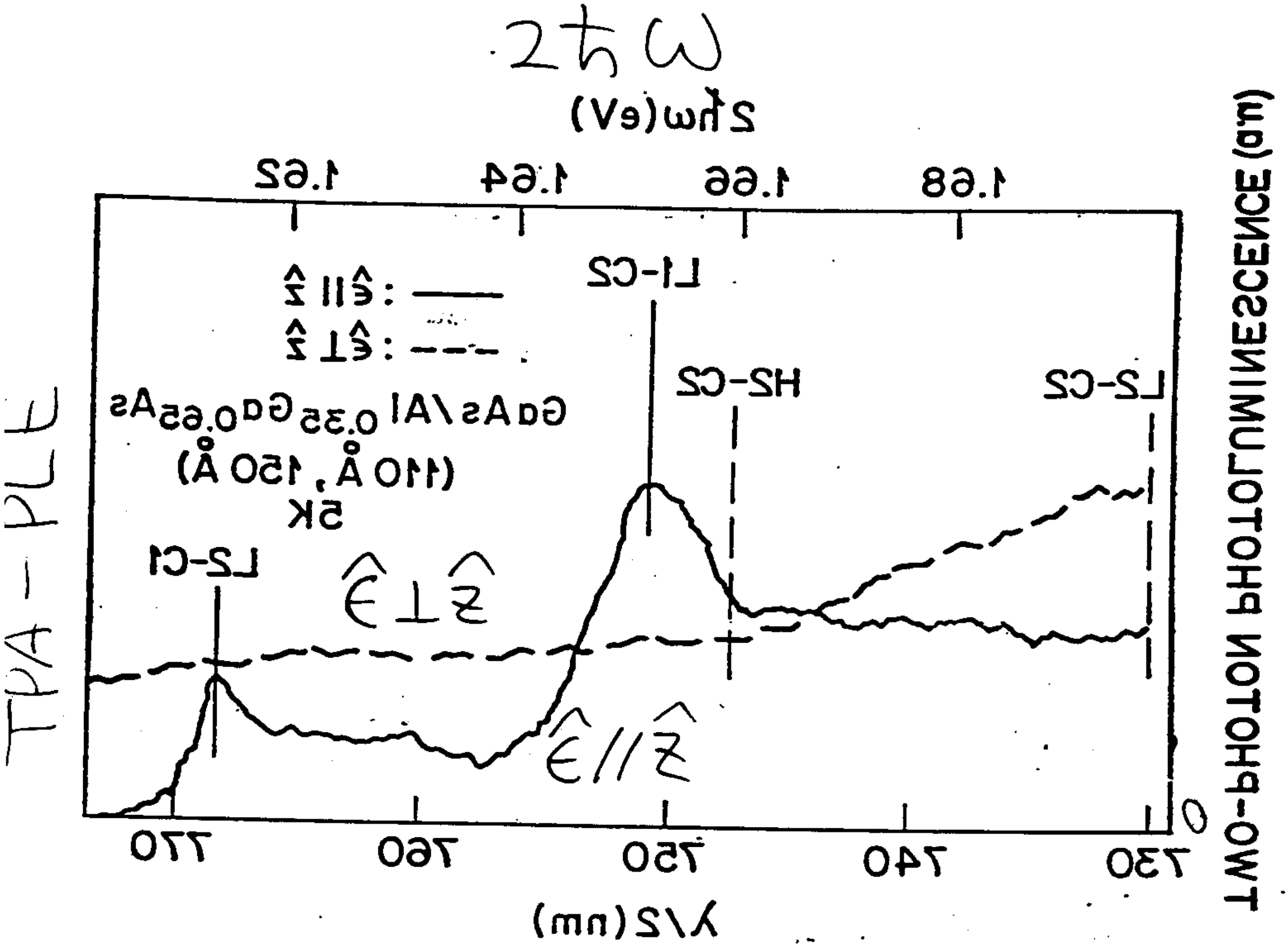


$$W_{TPA}^{(2)} \propto \sum_{v} B_v^{(2)} G_v^{(2)}$$



Height of ⊥ = Integral of Λ ÷ Γ (=10 meV)

K. Tai, A. Mysyrowicz, R.J. Fisher,
R.E. Slusher, A.Y. Cho, PRL 62 (1989) 1784



EXPERIMENT

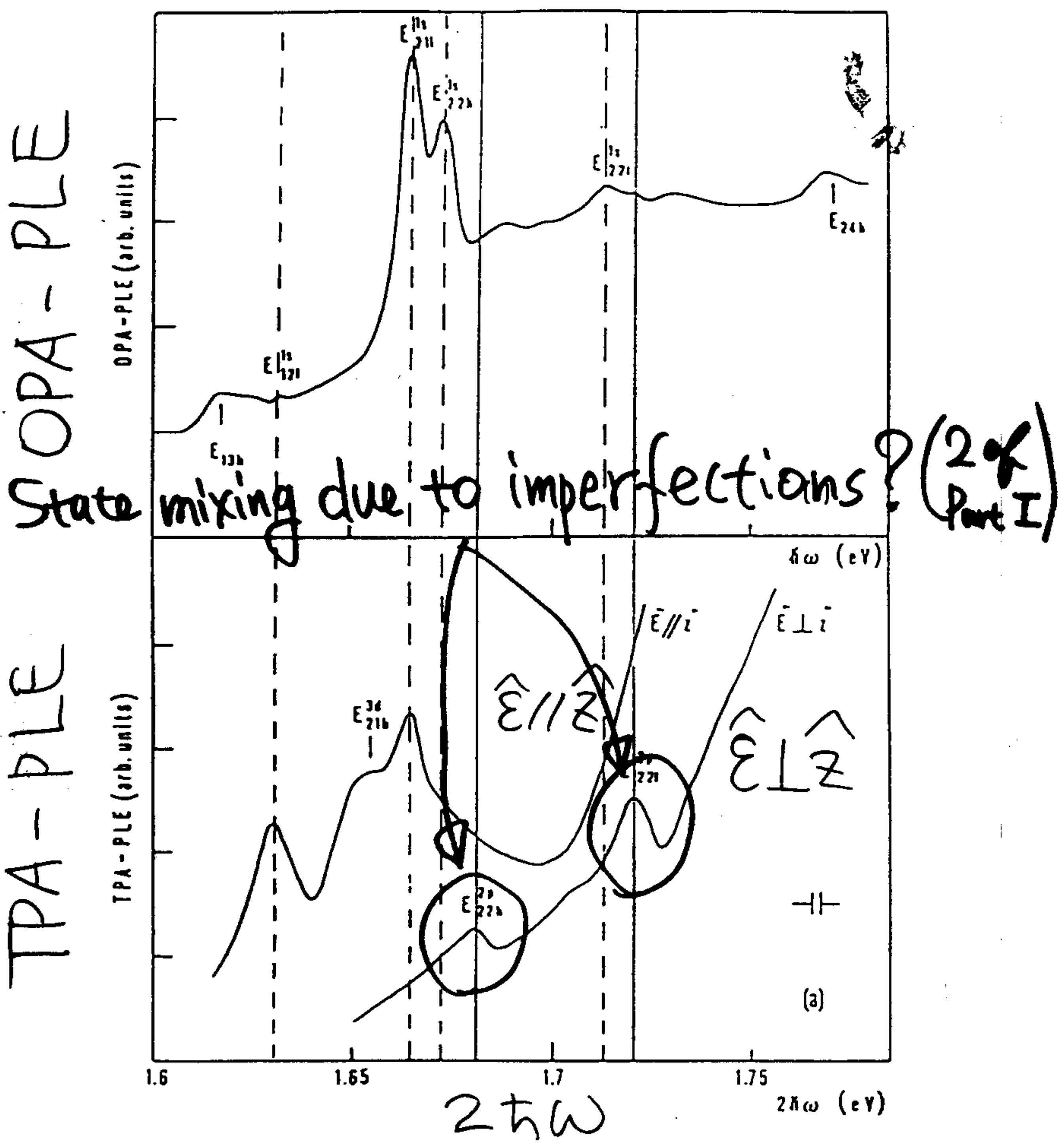
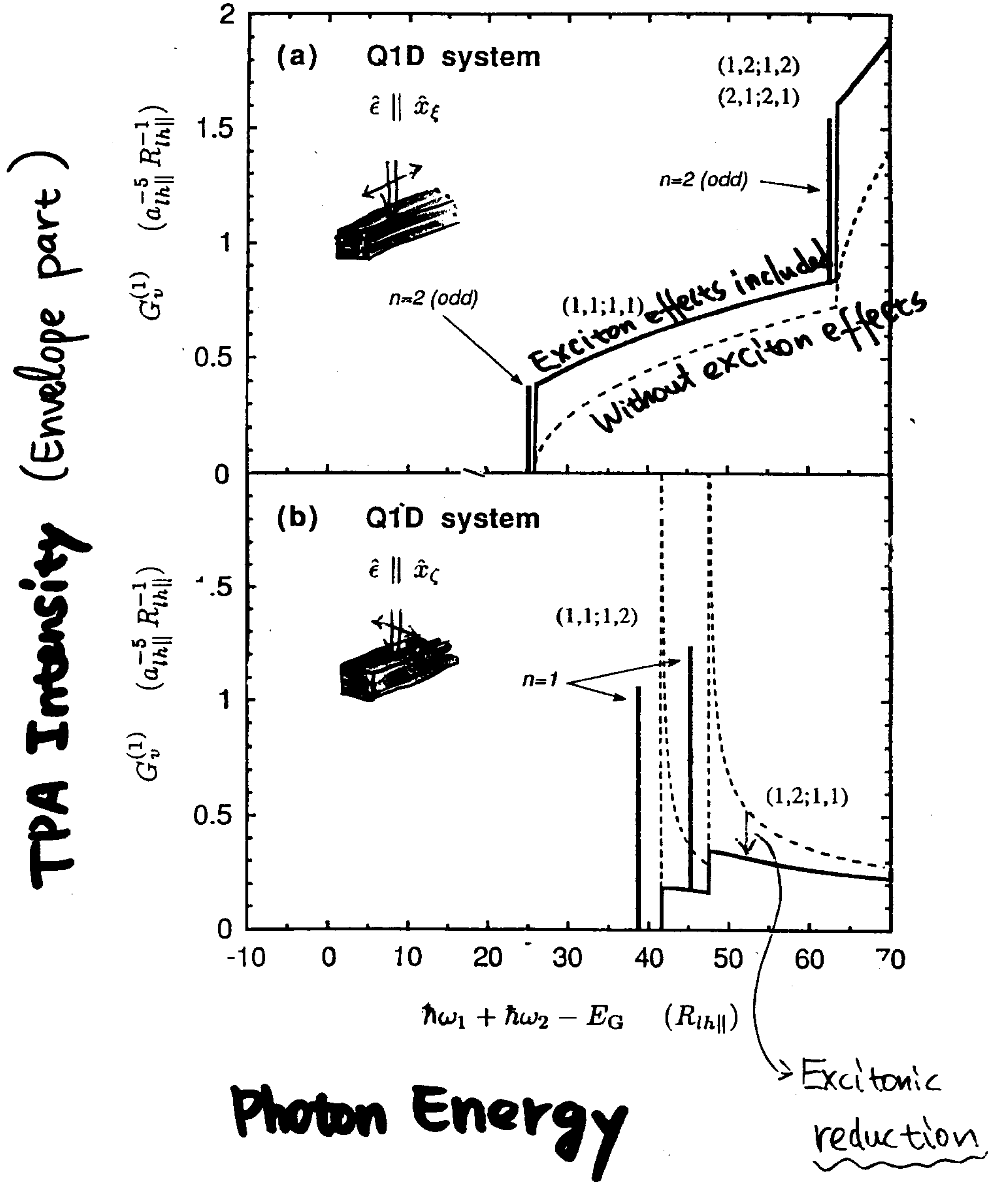


Fig. 1. (a) Two-photon absorption photoluminescence excitation spectra (TPA–PLE) in $E \parallel z$ and $E \perp z$ polarization configurations for the sample A. (b) One-photon absorption photoluminescence excitation spectra (OPA–PLE) for the same sample. Dashed lines indicate transitions occurring at the same energy in both the spectra ($1s$ state). Continuous lines indicate blue-shifted transitions involving excited excitonic states in the TPA–PLE spectrum.

I. M. Catalano, A. Cingolani, M. Lepore, R. Cingolani, K. Ploog, Solid State Commun. <u>71</u> (1989) 217

Γ = 10 meV is assumed for all discrete levels.

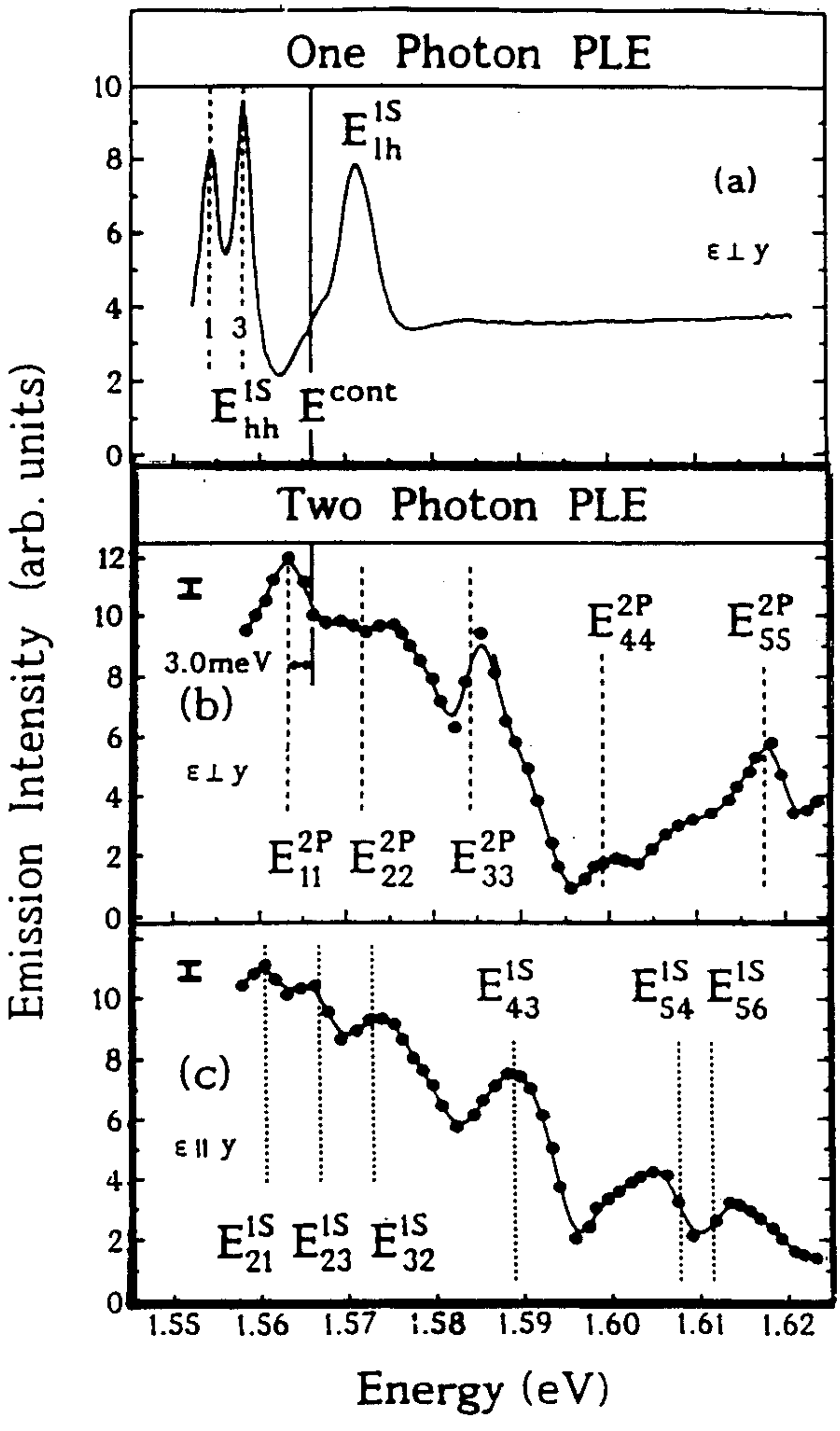


EXPERIMENT

OPA AND TPA SPECTRA of a wide QWR

R. Cingolani, M. Lepore, R. Tommasi, I. M. Catalano, H. Lage, D. Heitmann, K. Ploog, A. Shimizu, H. Sakaki, T. Ogawa, Phys. Rev. Lett. 69 (1992) 1276

$T = 10\,K$
PL detection at $E_{11}^{1S} = 1.554\,eV$



$L_\perp < a_B^{(1)}$ is NOT satisfied

$\hat{\varepsilon} \parallel \hat{x}$ Unconfined

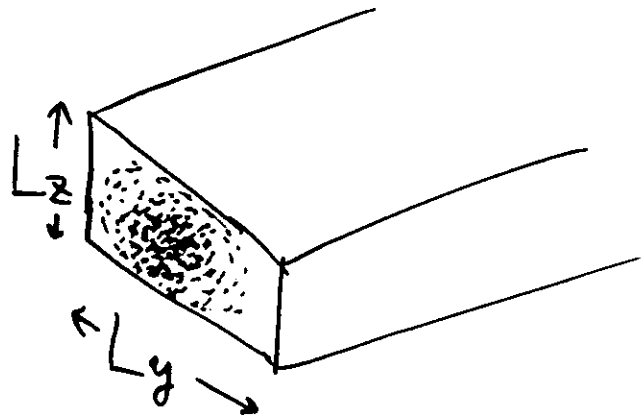
$\hat{\varepsilon} \parallel \hat{y}$ Weakly confined

?

TPA spectrum is anisotropic, but the strengths of the peaks are, on an average, almost isotropic.

T. Ogawa and A. Shimizu, PR B48 (1993) 4911

2. Dimensional Crossover



$$L_z < a_B^{(2)} \ll L_y \Rightarrow \text{Q2D exciton}$$

$$L_z, L_y < a_B^{(1)} \Rightarrow \text{Q1D excitons}$$

What happens when $L_z < a_B^{(1)} \lesssim L_y$?

Excitons in the Intermediate Regime

Assume z confinement is strong enough:

$$L_z^2 \ll L_y^2 \quad and \quad a^2 \ll L_z^2 \ll [a_B^{(2)}]^2$$

When L_y is large .... Q2D exciton with a quantized center-of-mass motion (Q2'D exciton)

$$\Psi_{nmN}^{(2')}(\vec{r}_e, \vec{r}_h; [\alpha_z; \beta_z])$$

2D relative motion

subbands

$$= \underbrace{\mathcal{G}_N(Y)}_{\text{center-of-mass motion}} U_{nm}^{(2)}(x, y; [\alpha_z; \beta_z]) \overbrace{\phi_{\alpha_z}(z_e)\,\phi_{\beta_z}(z_h)}^{\text{subbands}}$$

center-of-mass motion

When L_y is small .... Q1D exciton

$$\Psi_{n\sigma}^{(1)}(\vec{r}_e, \vec{r}_h; [\alpha_y, \alpha_z; \beta_y, \beta_z])$$

$$= U_{n\sigma}^{(1)}(x; [\alpha_y, \alpha_z; \beta_y, \beta_z])$$ ← 1D relative motion

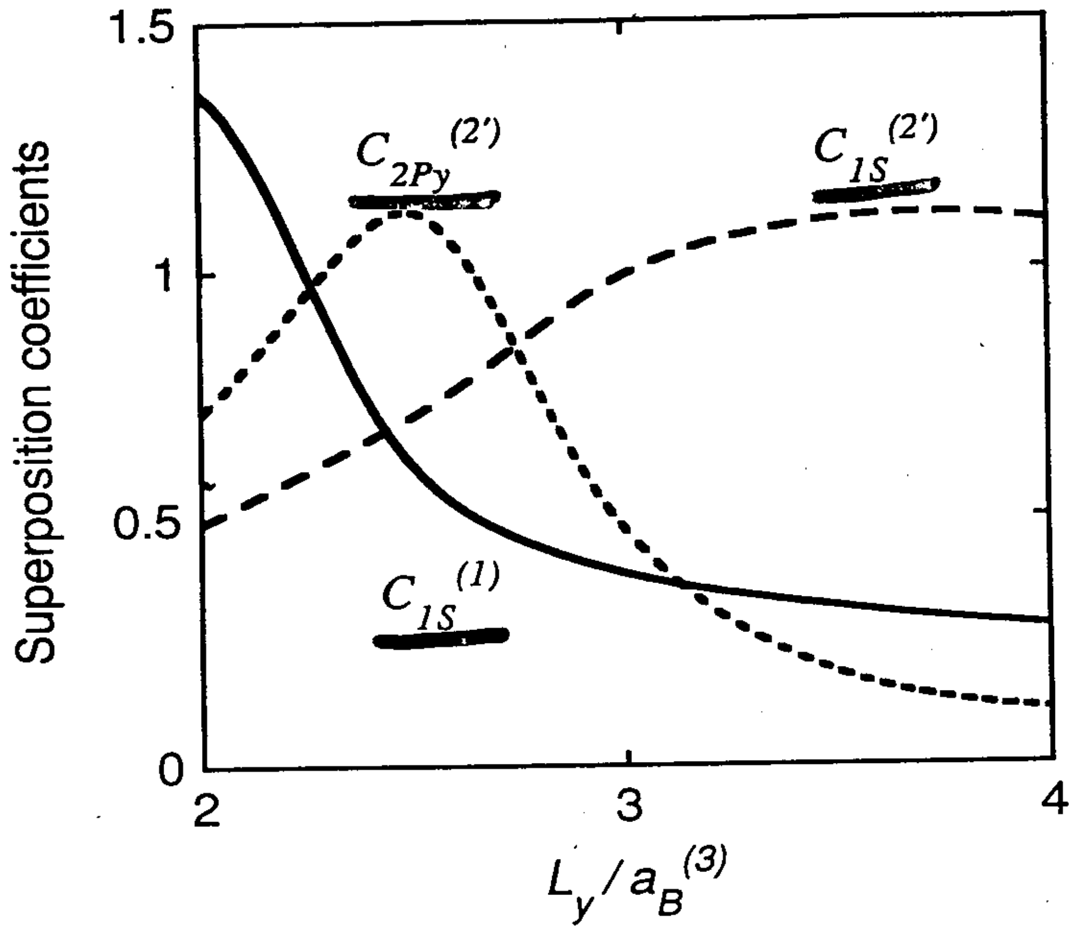
$$\times \underbrace{\phi_{\alpha_y}(y_e)\,\phi_{\beta_y}(y_h)\,\phi_{\alpha_z}(z_e)\,\phi_{\beta_z}(z_h)}_{\text{subbands}}$$

For intermediate values of L_y ... Q1-2D exciton

$$\Psi_{\sigma_x \sigma_y}^{(1-2)} \simeq \sum{}' C^{(1)} \Psi^{(1)} + \sum{}' C^{(2')} \Psi^{(2')}$$

sum over the states with the same parities

$$\Psi = \sum{}' \underline{C^{(1)}} \Psi^{(1)} + \sum{}' \underline{C^{(2')}} \Psi^{(2')}$$



1D like $\Longleftrightarrow$ 2D like

Note that
the approximation of a Q2D exciton with quantized center-of-mass motion is BAD when $L_y \lesssim 3\, a_B^{(3)}$

OPA and TPA rate of a Q1-2D exciton

$$W^{(1-2)} \simeq \ constant \times \left| \sum{}' C^{(1)} \sqrt{G^{(1)} B^{(2')}} \right.$$
$$\left. + \sum{}' C^{(2')} \sqrt{G^{(2')} B^{(2')}} \right|^2 ,$$

where

$$G^{(1)} = \text{Q1D envelope part},$$
$$G^{(2')} \doteq G^{(2)} \frac{1}{L_y} \left| \int \mathcal{G}_N(Y) dY \right|^2 .$$

→ You can NOT see N= even states in either OPA or TPA spectra

Since we have assumed $L_z^2 \ll L_y^2$,

$$B^{(2')} \simeq B^{(2)} .$$

Hence,

$$\boxed{\begin{aligned} W^{(1-2)} \simeq \ & constant \times B^{(2)} \left| \sum{}' C^{(1)} \sqrt{G^{(1)}} \right. \\ & \left. + \sum{}' C^{(2')} \sqrt{G^{(2)}} \frac{1}{\sqrt{L_y}} \int \mathcal{G}_N(Y) dY \right|^2 . \end{aligned}}$$

OPA in the intermediate regime

$(L_z^2 \ll L_y^2$ and $a^2 \ll L_z^2 \ll [a_B^{(2)}]^2)$

$$W_{OPA}^{(1-2)} \simeq constant \times B^{(2)} \left| \sum{}' C^{(1)} \sqrt{G_{OPA}^{(1)}} + \sum{}' C^{(2')} \sqrt{G_{OPA}^{(2)}} \frac{1}{\sqrt{L_y}} \int \mathcal{G}_N(Y) dY \right|^2 .$$

- Almost isotropic in the xy plane.
- The oscillator strength becomes insensitive to the state mixing. $\longrightarrow$ No sharp dependence on L_y.

$\boxed{\text{The OPA spectrum becomes similar to the Q2D spectrum.}}$

TPA in the intermediate regime

$(L_z^2 \ll L_y^2$ and $a^2 \ll L_z^2 \ll [a_B^{(2)}]^2)$

$$W_{TPA}^{(1-2)} \simeq constant \times B^{(2)} \left| \sum{}' C^{(1)} \sqrt{G_{TPA}^{(1)}} \right.$$

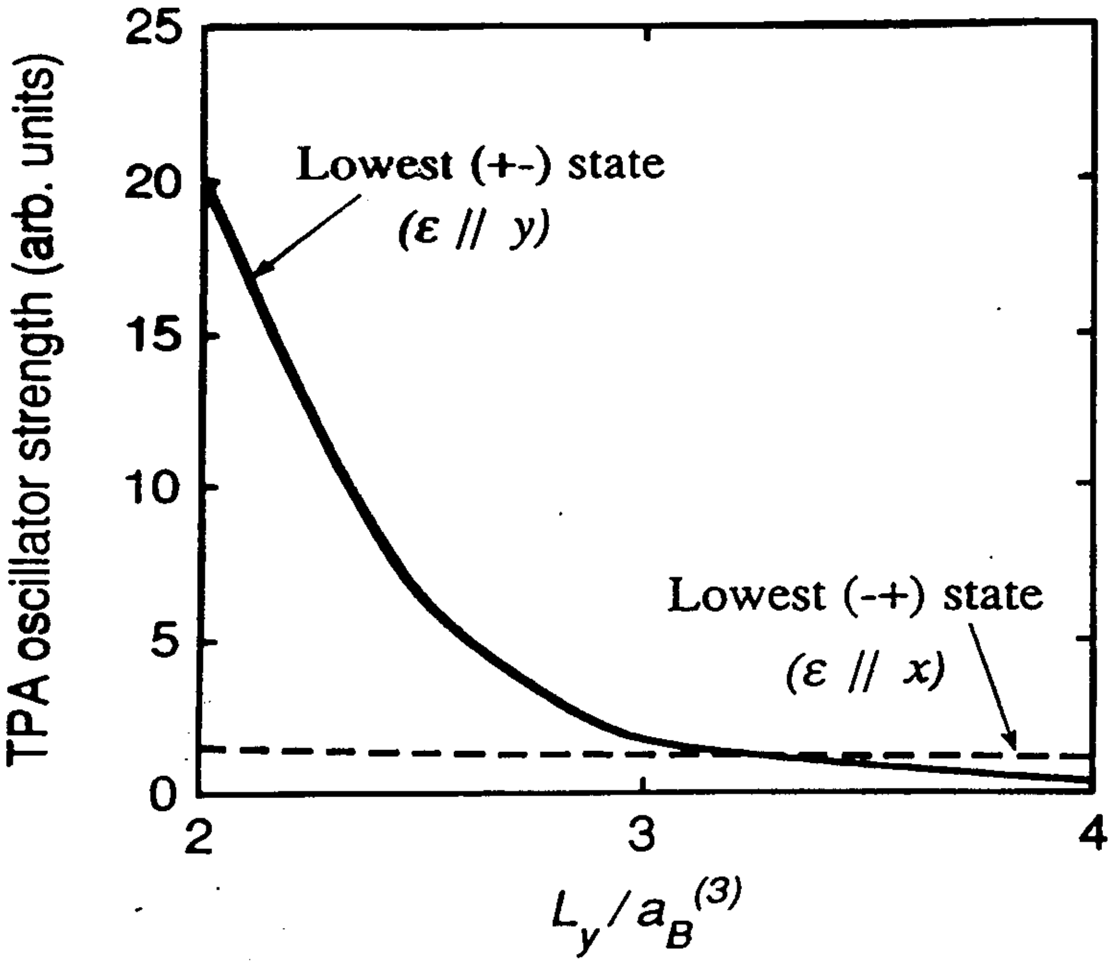
$\leftarrow xy$ anisotropy

$$\left. + \sum{}' C^{(2')} \sqrt{G_{TPA}^{(2)}} \frac{1}{\sqrt{L_y}} \int \mathcal{G}_N(Y) dY \right|^2 .$$

NO xy anisotropy

• The spectrum is very anisotropic for small L_y (for which $C^{(1)}$'s become large), and almost isotropic for large L_y (where $C^{(2')}$'s become dominant).

• The spectrum varies drastically, in both anisotropy and oscillator strength, as a function of L_y.



1D like ⟺ 2D like

For an intermediate value of Ly,
the TPA spectrum becomes
anistropic (in peak positions, etc.)
but the strengths of the peaks are
almost isotropic, on an average.

Concluding Remarks of 2 of Part I.

• Similar crossover effects will also occur in quantum wells and boxes when they are not small enough.

• Imperfections in their structures can also induce a similar effect.

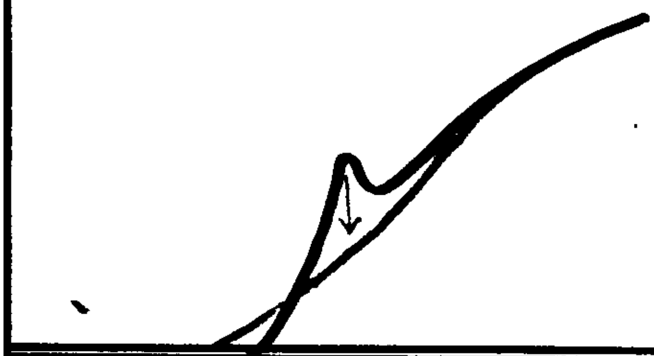
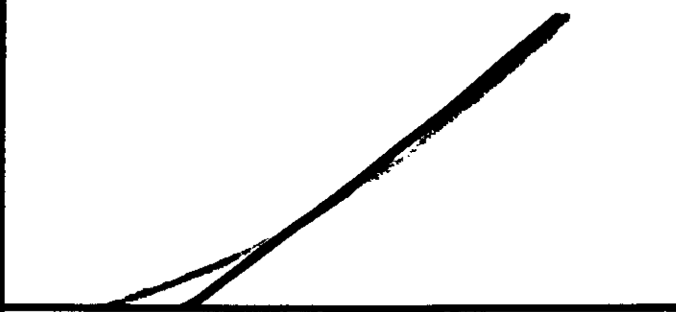
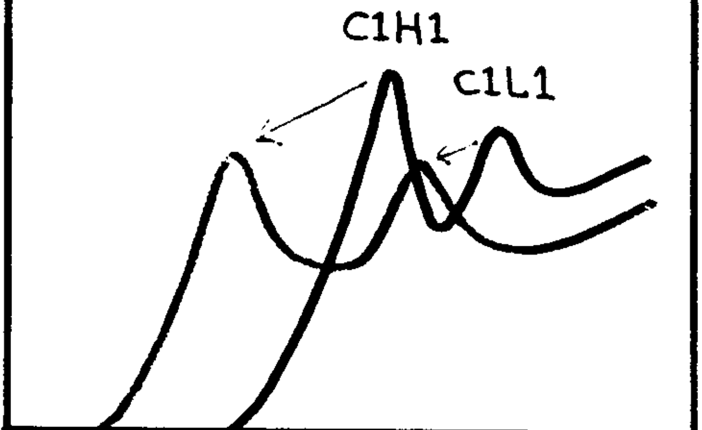
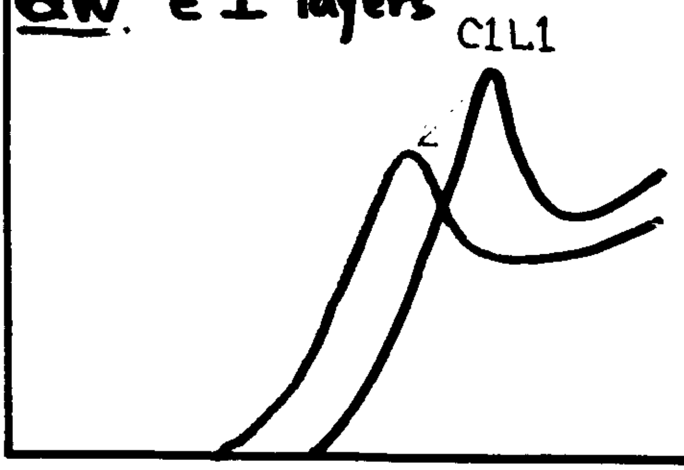
• Our argument relies completely on the exciton effects:

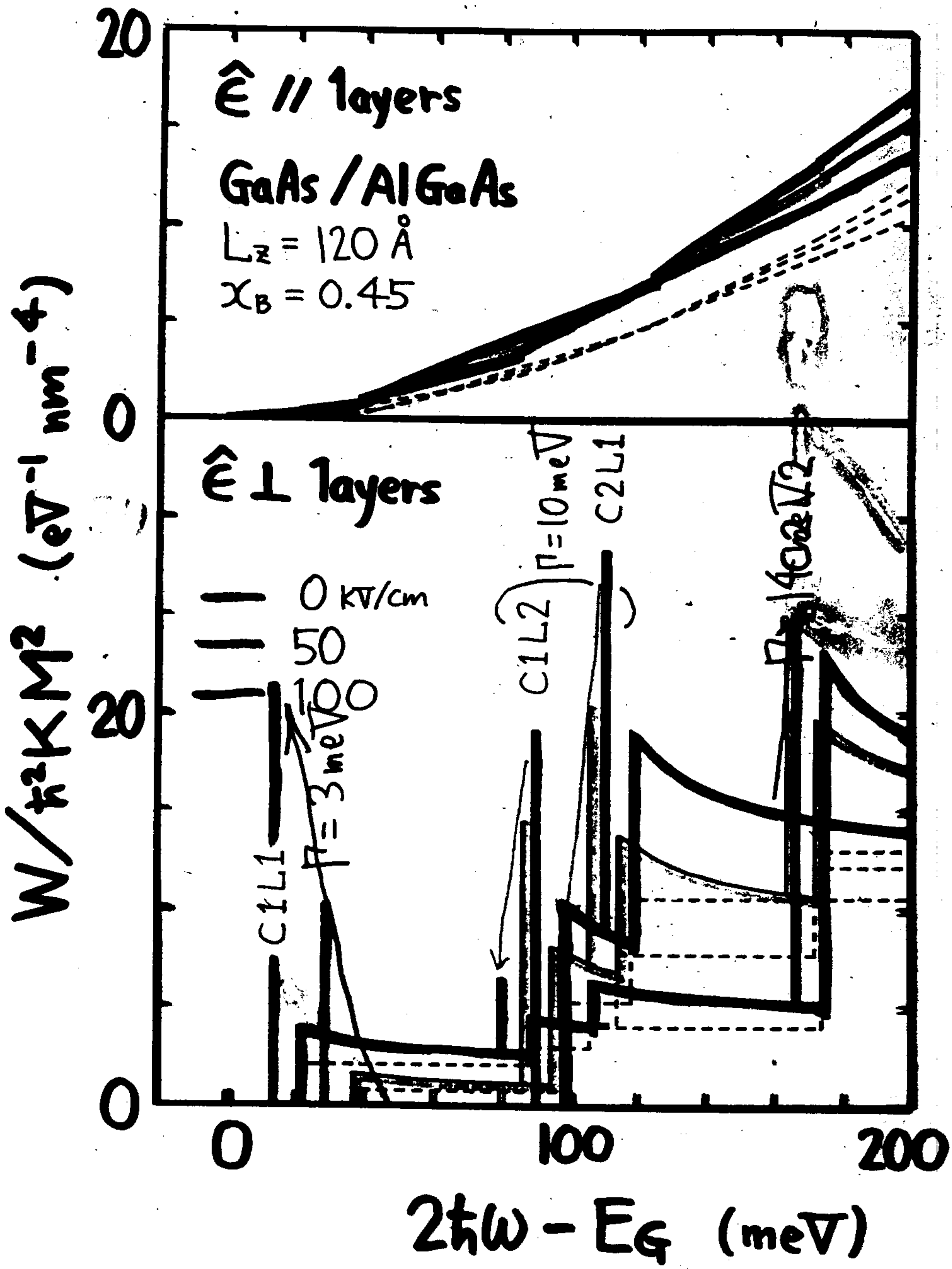
Without exciton effects

$\longrightarrow$ No length scale $a_B^{(d)}$

$\longrightarrow$ No qualitative change when L_y varies.

Photon Absorption in Direct-Allowed-Gap Semiconductors

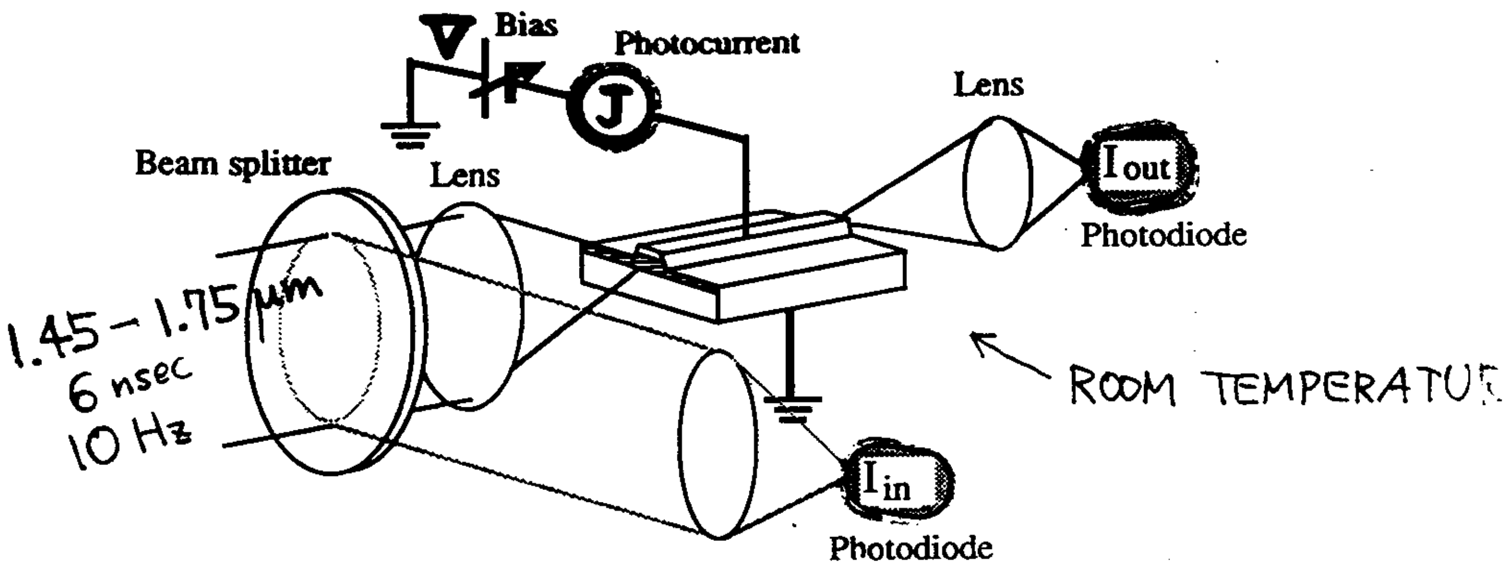
One-Photon Absorption $\hbar\omega \sim E_G$	Two-Photon Absorption $\hbar\omega \sim E_G/2$
Bulk crystal 	
QW $\hat{\varepsilon}$ // layers 	
QW $\hat{\varepsilon} \perp$ layers 	

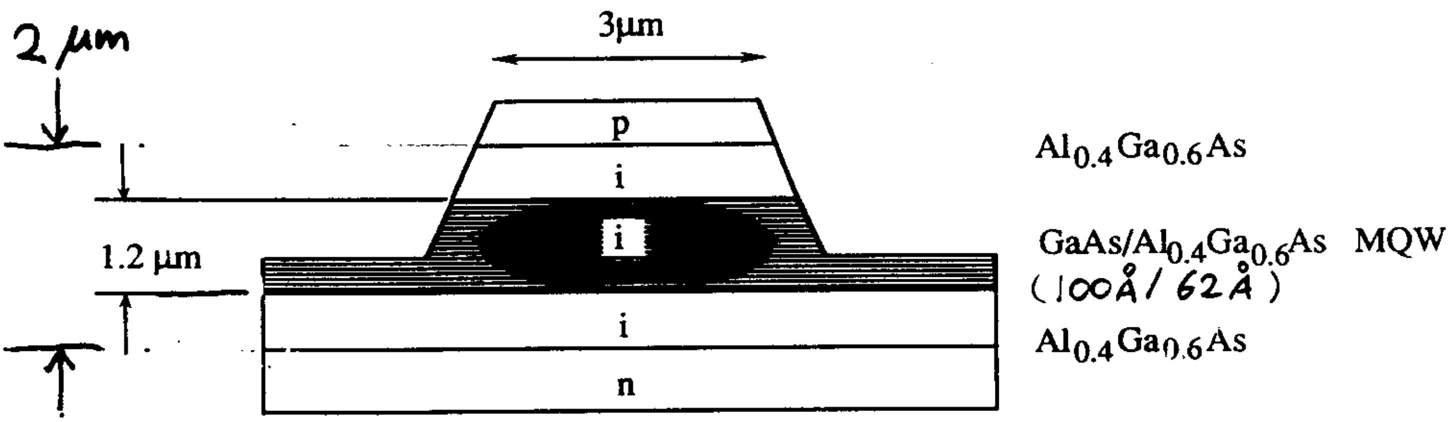


Ê // layers
GaAs / AlGaAs
Lz = 120 Å
xB = 0.45
Ê ⊥ layers
0 kV/cm
50
100
C1L1
Γ = 3 meV
C1L2
Γ = 10 meV
C2L1
Γ = 14 meV
20
0
20
0
0
100
200
W/ħ²KM² (eV⁻¹ nm⁻⁴)
2ħω − EG (meV)

Estimation of $\alpha_2(V)$ at each wavelength

- J/I_{out} versus I_{out}
- I_{out}/I_{in} versus I_{in}





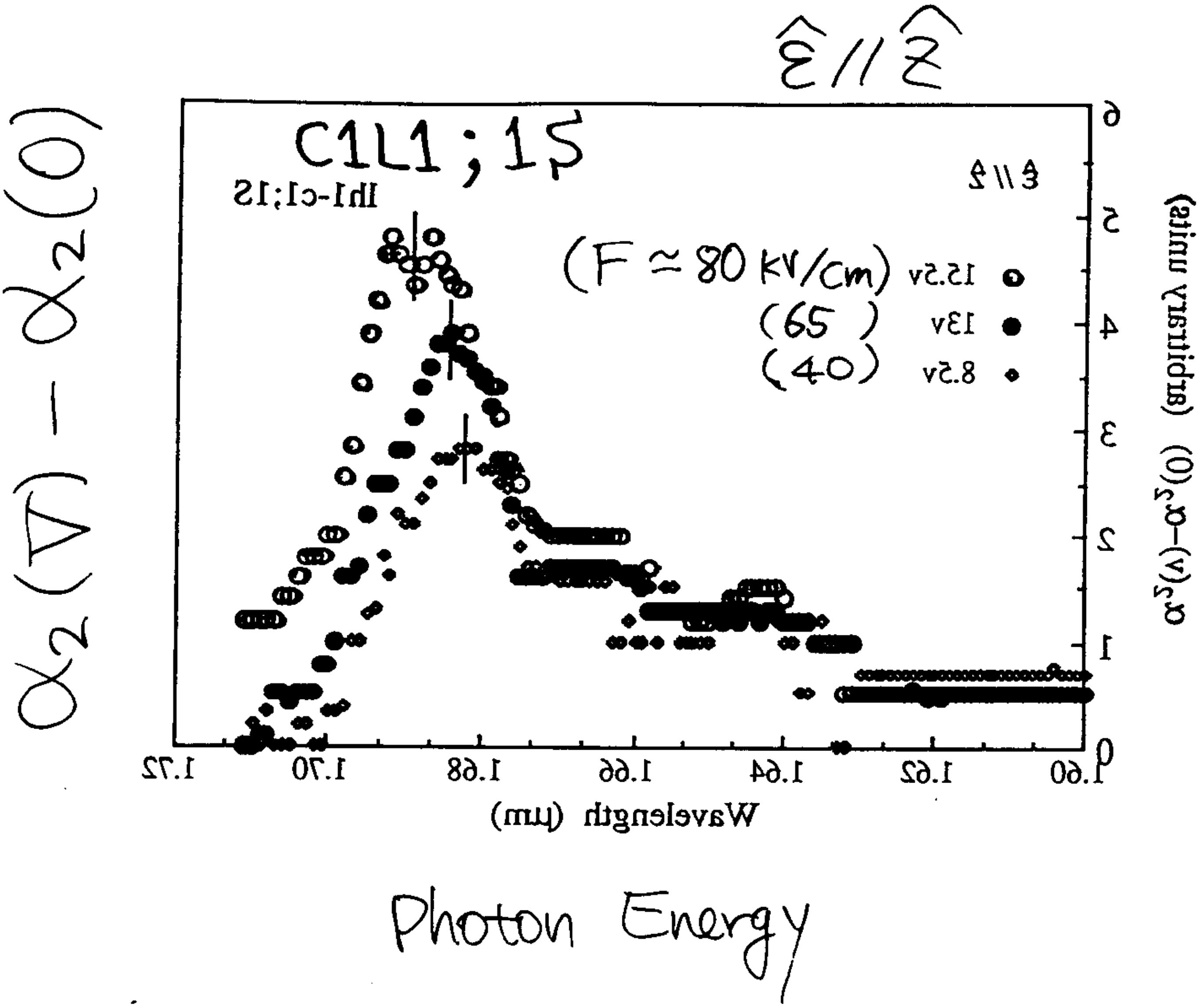
- Two-dimensional confinement

→ No self-focusing effects.
No surface effects
Good S/N

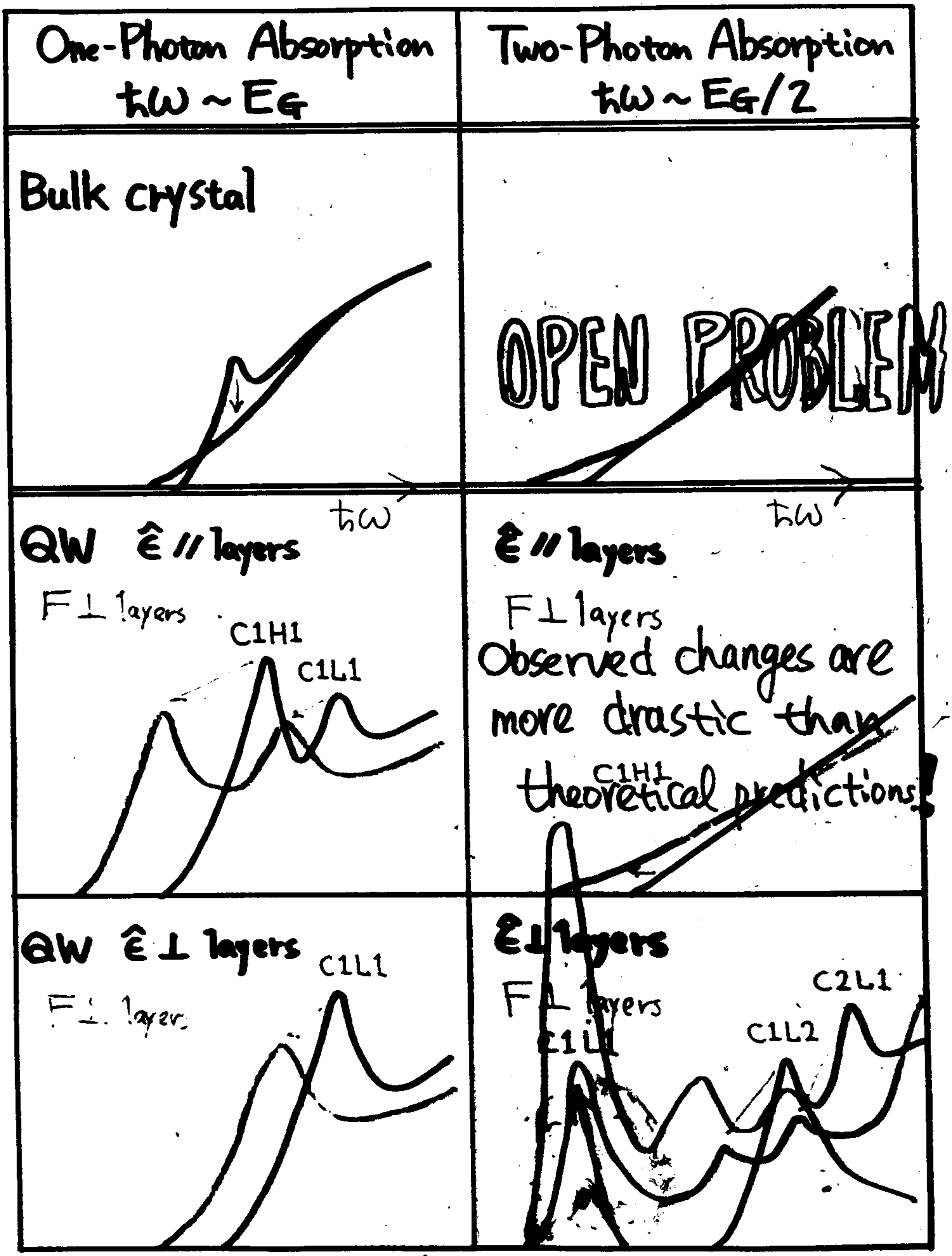
K. Fujii, A. Shimizu, J. Bergquist and T. Sawada, PRL 65 (1990) 1808

K. Fujii, A. Shimizu, J. Bergquist, T. Sawada

Phys. Rev. Lett. 65 (1990) 1808



Photon Absorption in Direct-Gap Semiconductors



Quantum-Confined Stark Effect (QCSE) Miller et al. (1984)

QCSE on TPA
A. Shimizu, PR B40 (1989) 1403

Summary of Part I

OPA and TPA of low-D excitonic systems

1. General formula for QdD excitonic systems

- Sum over intermediate should be taken carefully.
- TPA spectroscopy is much more sensitive probe of the dimensionality than the OPA spectroscopy.
- Agree with experiments on quantum well structures.

2. Theory of dimensional crossover effects

- Drastic changes of TPA spectrum as the lateral confinement size varies across the excitonic Bohr radius.
- Explain a puzzling experimental result on a wide quantum wire.

3. TPA of electrically-biased QWSs

• Drastic changes are predicted.

• Confirmed by experiment, but the observed changes are larger than the prediction.

$\longrightarrow$ **Open problem!**

Part II

Quantum non-demolition photodetector composed of a quantum-wire electron interferometer

Akira Shimizu

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1. Motivation
2. Quantized radiation field.
3. What is QND measurement?
4. QWR interferometer as a QND photodetector.
5. Backaction of the measurement.
6. Measurement error.
7. Concluding remarks.

A BIRD'S-EYE VIEW

CONDENSED-MATTER PHYSICS

Dense electrons without e.m. fields
(quantized)

↓

Dense electrons in classical e.m. f.
(quantized)

↓

$\boxed{\text{Dense electrons (quantized)} \times \text{Quantized e.m. fields}}$

↑

Quantized e.m. f. × Atoms, or
Effective Media

↑

Classical e.m.f. × Atoms, or
Effective Media

OPTICAL PHYSICS

Classical :

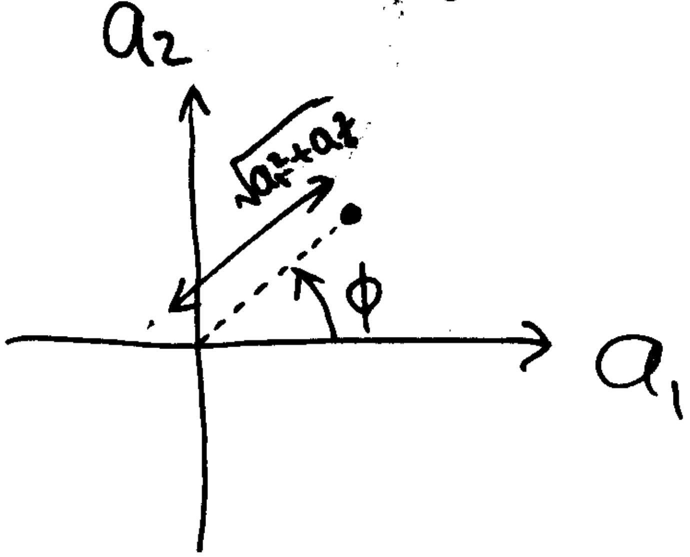
$$\mathcal{E}(t) = \vec{\epsilon}\,\mathcal{E}_0 \left[a e^{-i\omega t} + a^* e^{+i\omega t} \right]$$

$a_1 = \frac{a + a^*}{2}$

$a_2 = \frac{a - a^*}{2i}$

$$= \vec{\epsilon}\,\mathcal{E}_0 \left[a_1 \cos\omega t + a_2 \sin\omega t \right]$$

$$= \vec{\epsilon}\,\mathcal{E}_0 \sqrt{a_1^2 + a_2^2}\, \cos(\omega t + \phi)$$



$$\tan\phi = \frac{a_2}{a_1}$$

Quantum :

$$\hat{\mathcal{E}}(t) = \vec{\epsilon}\,\mathcal{E}_0 \left[\hat{a} e^{-i\omega t} + \hat{a}^{+} e^{+i\omega t} \right]$$

$\hat{a}_1 = \frac{\hat{a} + \hat{a}^{+}}{2}$

$\hat{a}_2 = \frac{\hat{a} - \hat{a}^{+}}{2i}$

$$= \vec{\epsilon}\,\mathcal{E}_0 \left[\hat{a}_1 \cos\omega t + \hat{a}_2 \sin\omega t \right]$$

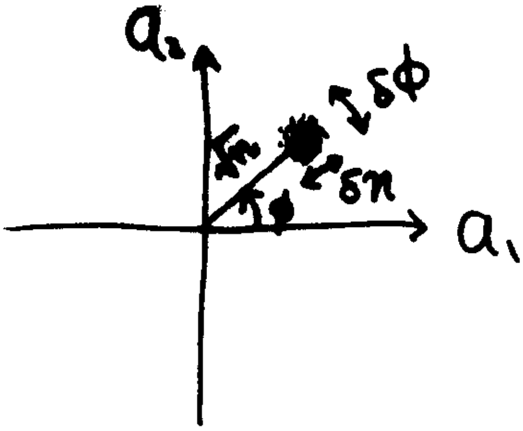
$$\hat{a}|0\rangle = 0\,, \quad |n\rangle = \frac{1}{\sqrt{n!}} (\hat{a}^{+})^n |0\rangle$$

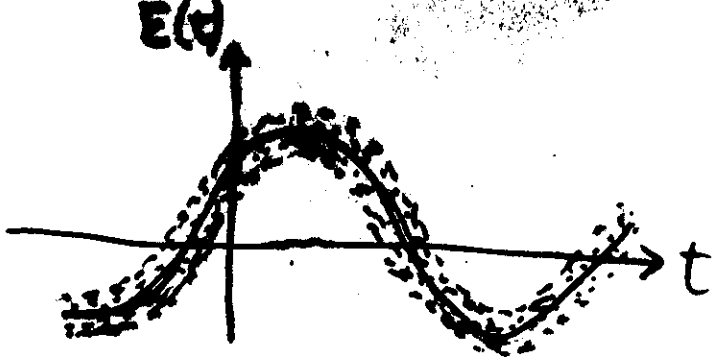
$$|\psi_{ph}\rangle = \sum_n a_n |n\rangle$$

$$\vec{\mathcal{E}}(t) = \vec{\epsilon}\,\mathcal{E}_0\left[\hat{a}_1 \cos\omega t + \hat{a}_2 \sin\omega t\right]$$

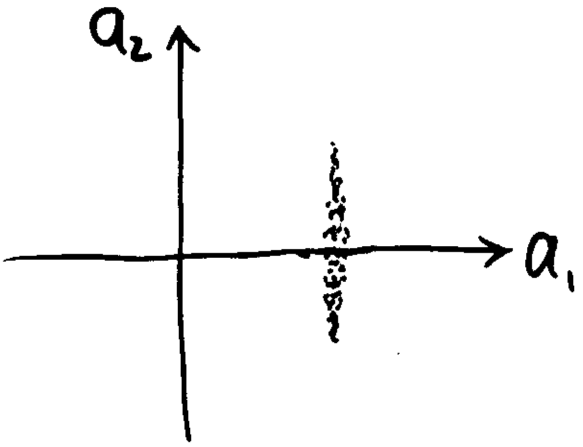
$$\delta a_1 \cdot \delta a_2 \geq \frac{1}{4} \longrightarrow \delta n \cdot \delta\phi \geq \frac{1}{2}$$

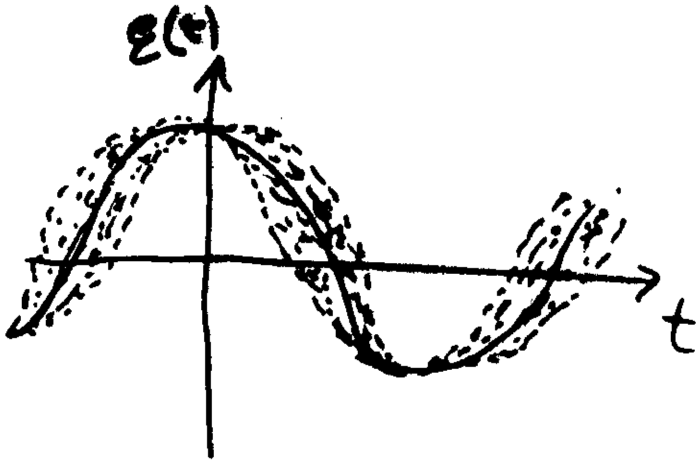
$\delta a_1 = \delta a_2 = \frac{1}{2}$ (Coherent state $e^{-\frac{1}{2}|\alpha|^2}\sum_n \frac{\alpha^n}{\sqrt{n!}}|n\rangle$)



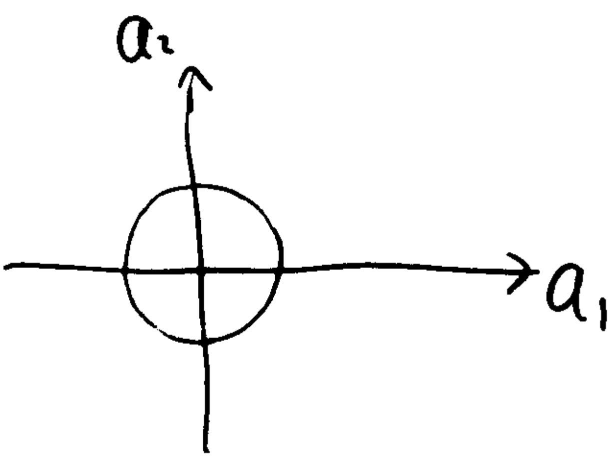


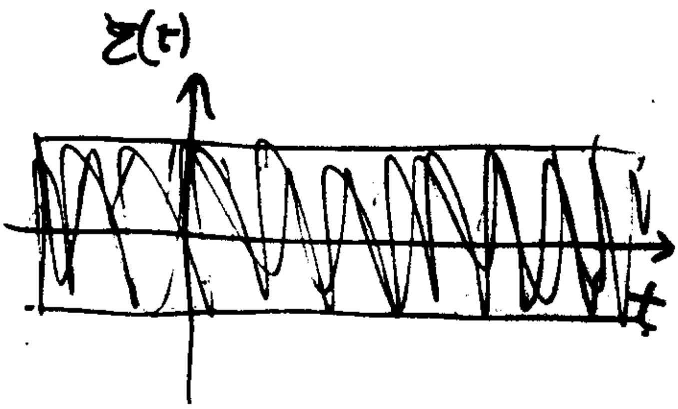
$\delta a_1 < \delta a_2$ (squeezed state)





$\delta n = 0,\ \delta\phi = \infty$ (number state $|n\rangle$)



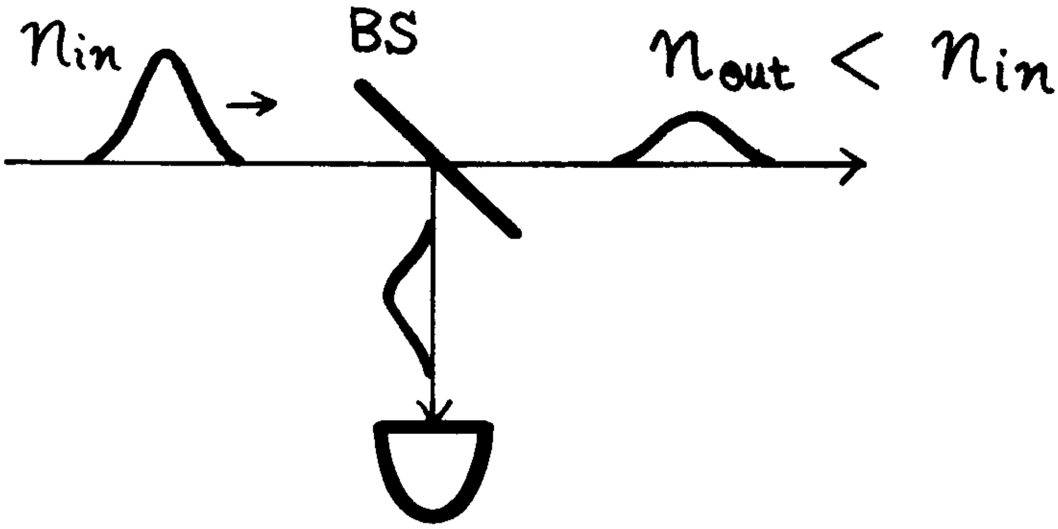


Measurement of Photon Number

Demolition Detectors : $\text{Prob}_{\text{out}}(n) \neq \text{Prob}_{\text{in}}(n)$

a)

b)



Quantum Non-Demolition (QND) Detectors :

$$\text{Prob}_{\text{out}}(n) = \text{Prob}_{\text{in}}(n) \quad \text{(for the ensemble)}$$

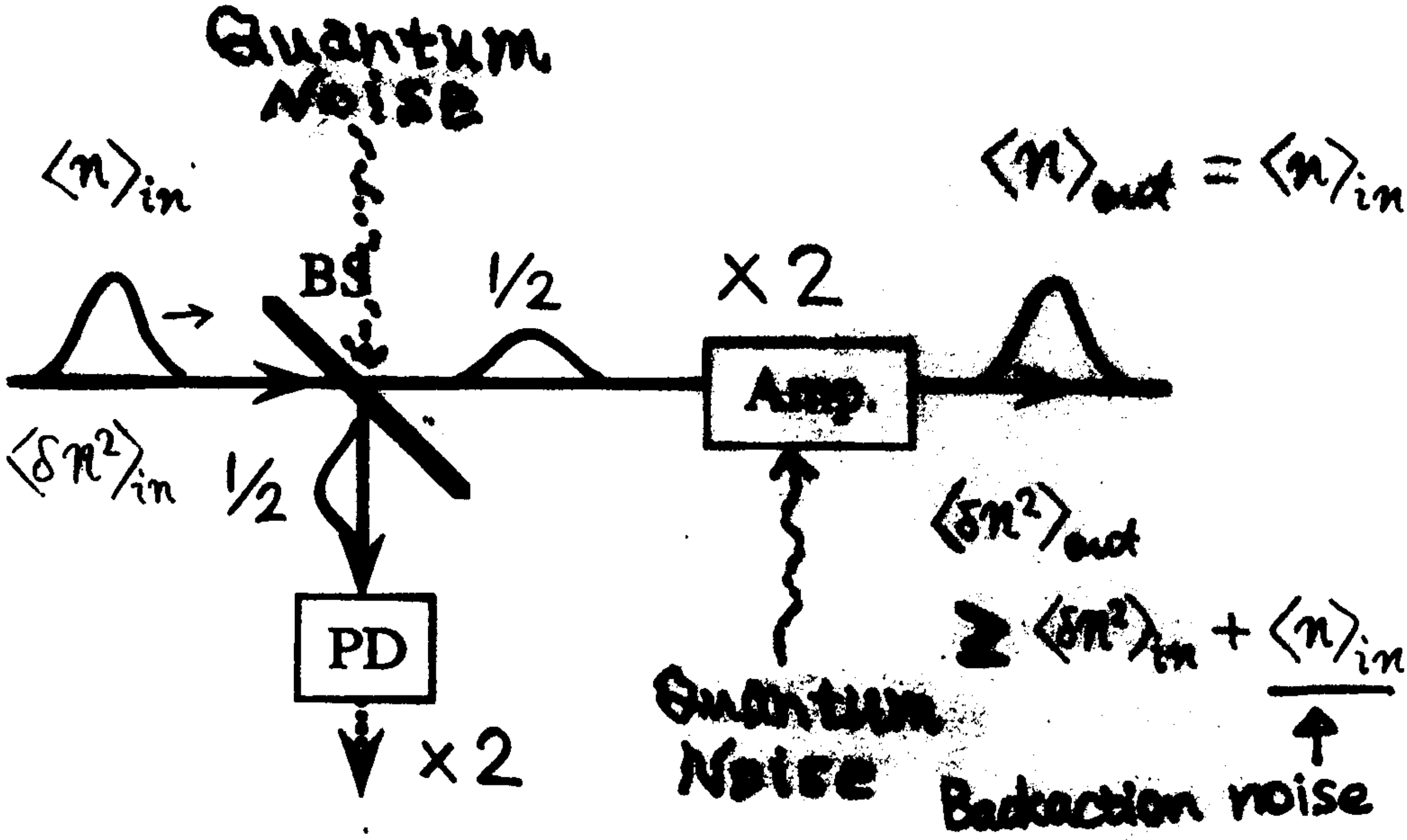
c)

▷ Measure n without absorption.

▷ Information encoded in n is all preserved.

A Classical Absorption-Free Photodetector

— A Non-QND Example



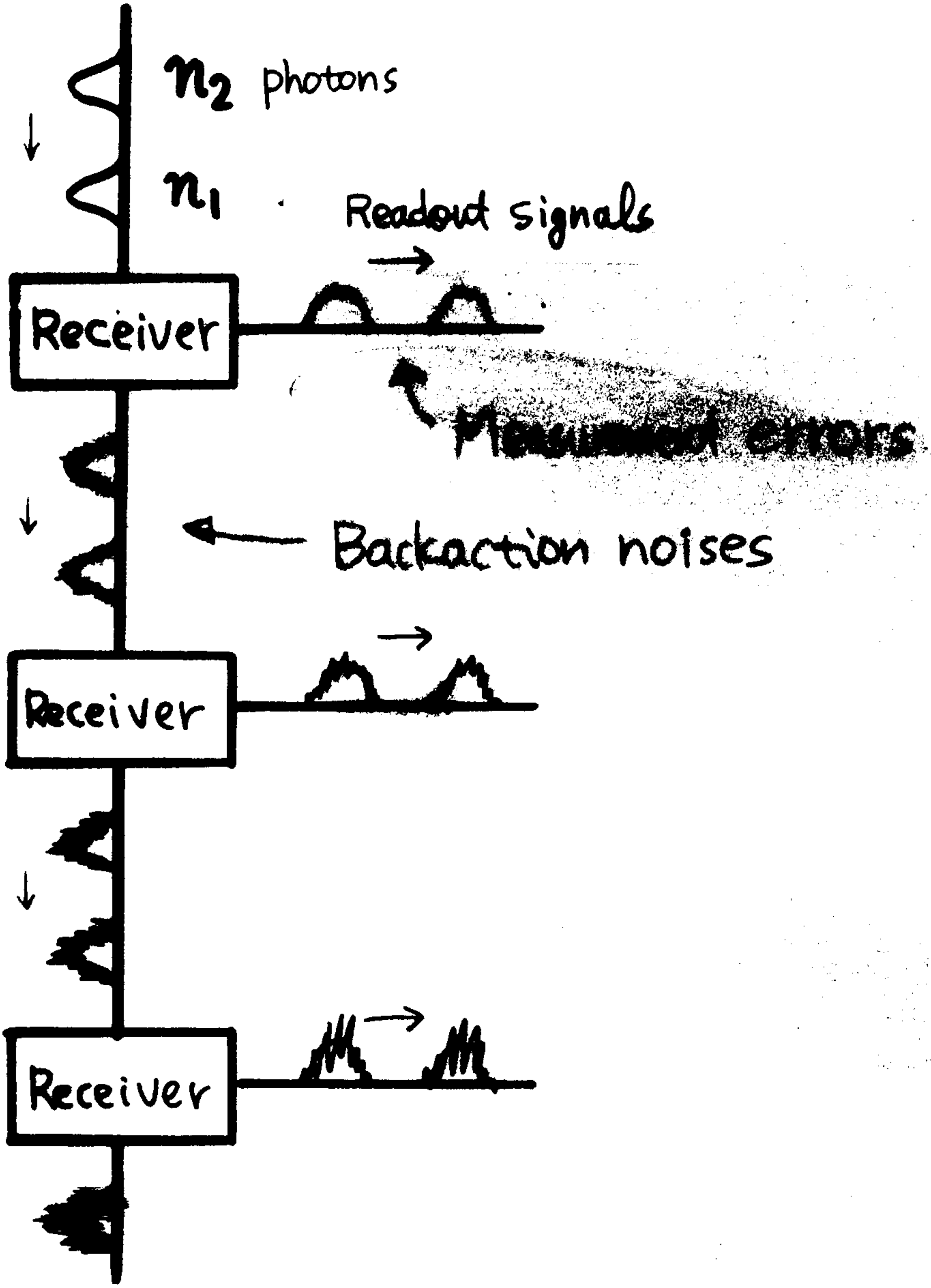
$$\langle n_{read} \rangle = \langle n \rangle_{in}$$

$$\langle \delta n^2_{read} \rangle \geq \langle \delta n^2 \rangle_{in} + \underline{\langle n \rangle_{in}}$$

Measurement error

Absorption free $\underset{\Leftarrow}{\not\Rightarrow}$ QND

Quantum Optical Communication



QND photodetectors using nonlinear optics

Unruh ('78), Milburn & Walls ('83), Imoto et al. ('85) Yurke ('85), Levenson et al. ('86), La Porta et al. ('89), Watanabe et al. ('89), Haus et al. ('89), Grangier et al. ('91)

Typical size > 1 m, Large energy consumption

Classical absorption-free photodetectors using mesoscopic interferometers

Yamanishi et al. ('88, '90), Shimizu et al. ('90)

Typical size $\sim$ 1 μm, Low energy consumption

QND photodetectors using mesoscopic interferometers?

Problem : Electrons as a probe $\Rightarrow$ $[\hat{H}_I, \hat{n}] \neq 0$

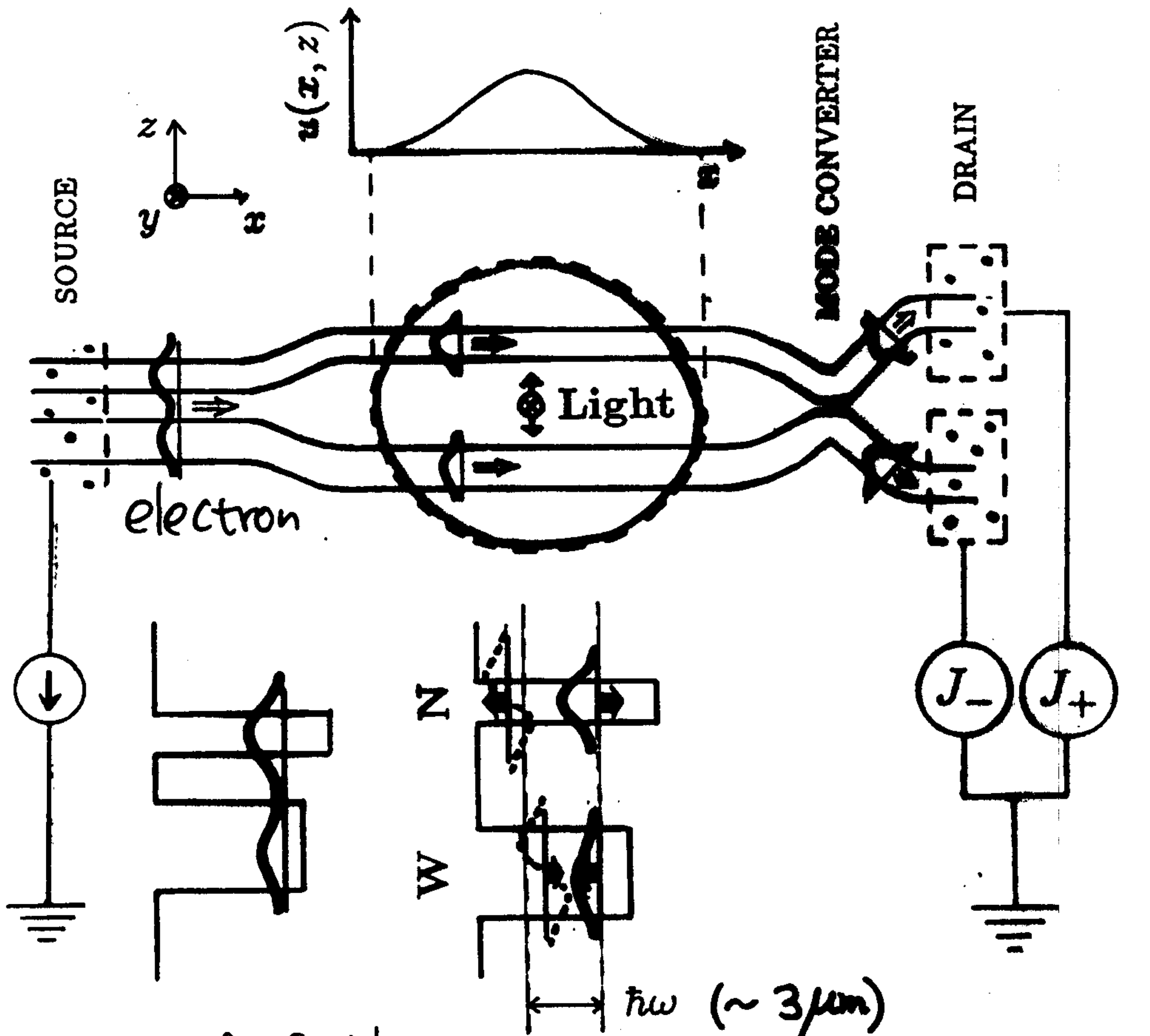
whereas $[\hat{H}_I, \hat{n}] = 0$ was the standard criterion for QND.

Solution : $[\hat{H}_I, \hat{n}] = 0$ is too strong!

General discussion is given in A. Shimizu & K. Fujita, Proc. ISQM-Tokyo '92 (JJAP Series 9, 1993)

Semiclassical analysis : PR B42 ('90) 9248.

Fully-quantum analysis : Proc. 17th IQEC, May '90.
PR A43 ('91) 3819.



Optical field

⇩

Virtual excitation of electrons

⇩

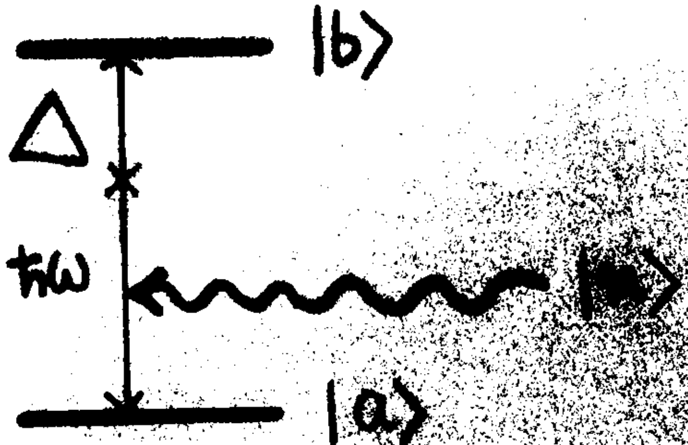
Phase shifts of electrons $\propto n$

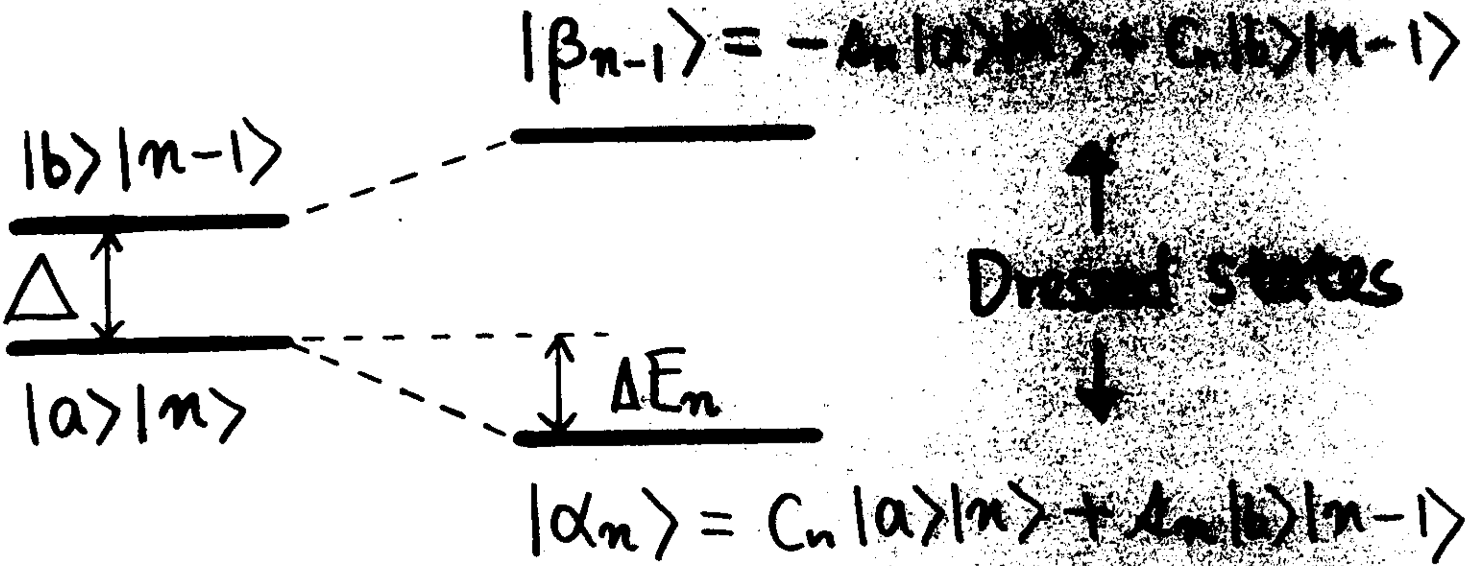
⇩

Modulation of interference currents

Optical Stark Effect

$|\Delta| \ll \hbar\omega$



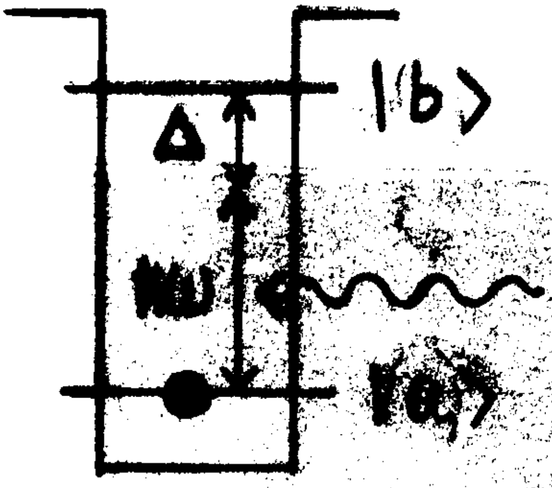


$$
\begin{cases}
\Delta E_n \simeq \gamma^2 \dfrac{n}{\Delta} & : \text{Quadratic Stark Shift} \\[2ex]
\left|\dfrac{s_n}{c_n}\right|^2 \simeq \Delta E_n / \Delta
\end{cases}
$$

$\Delta E_n \gtrless 0$ for $\Delta \gtrless 0$.

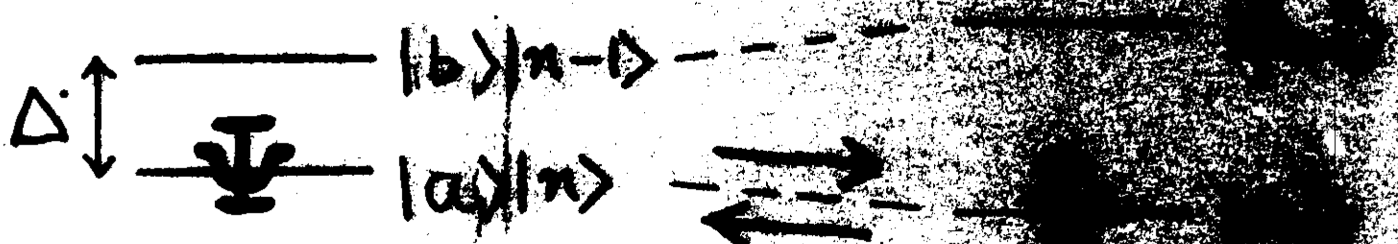
Intersubband optical Stark effect

(Optical quantum-confined Stark effect
Fröhlich et al., Phys. Rev. Lett. 59 ('87) 1748)



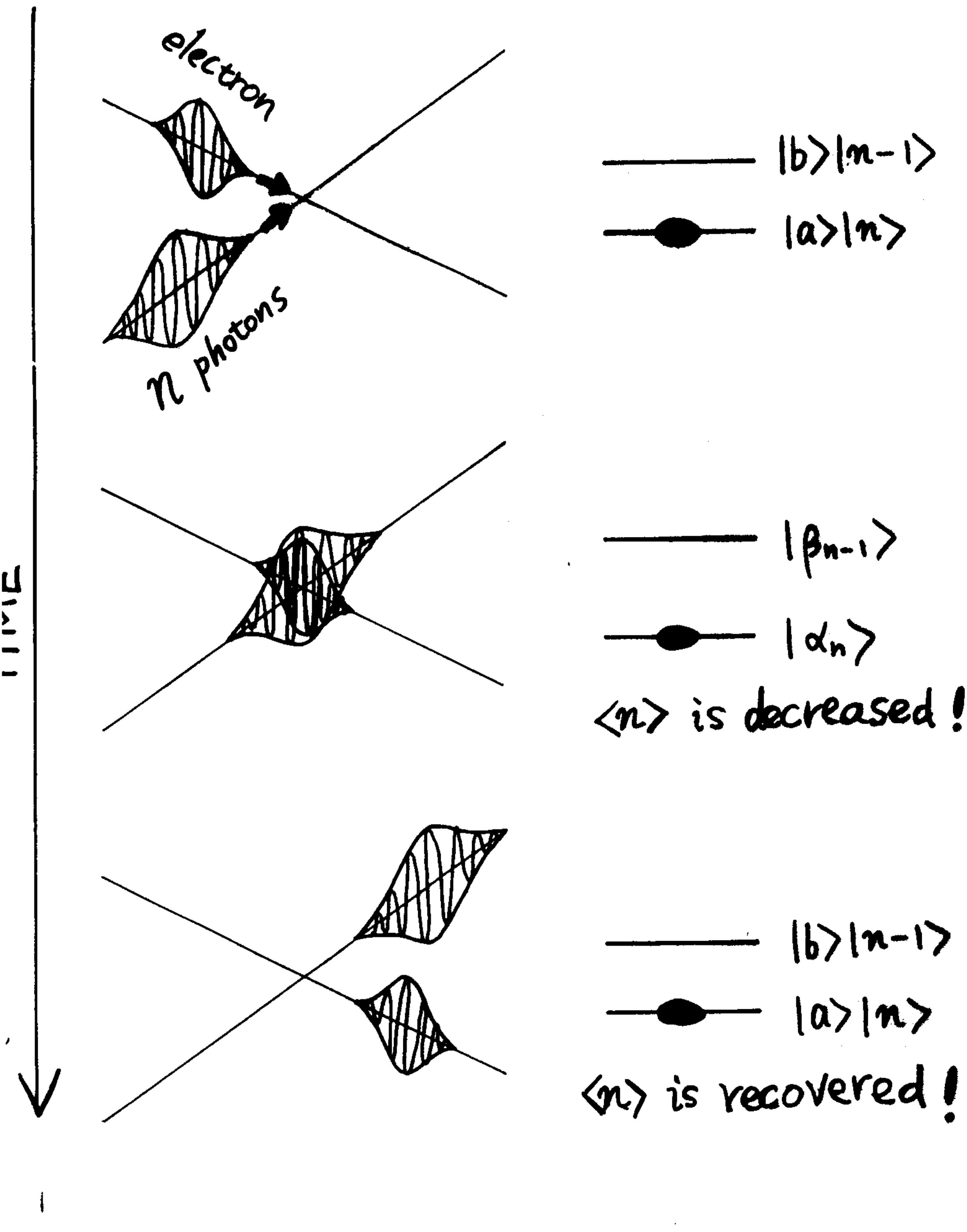
Basic idea: adiabatic [illegible]

$$\hat{H}_I = 0 \quad \rightleftarrows \quad [illegible]$$

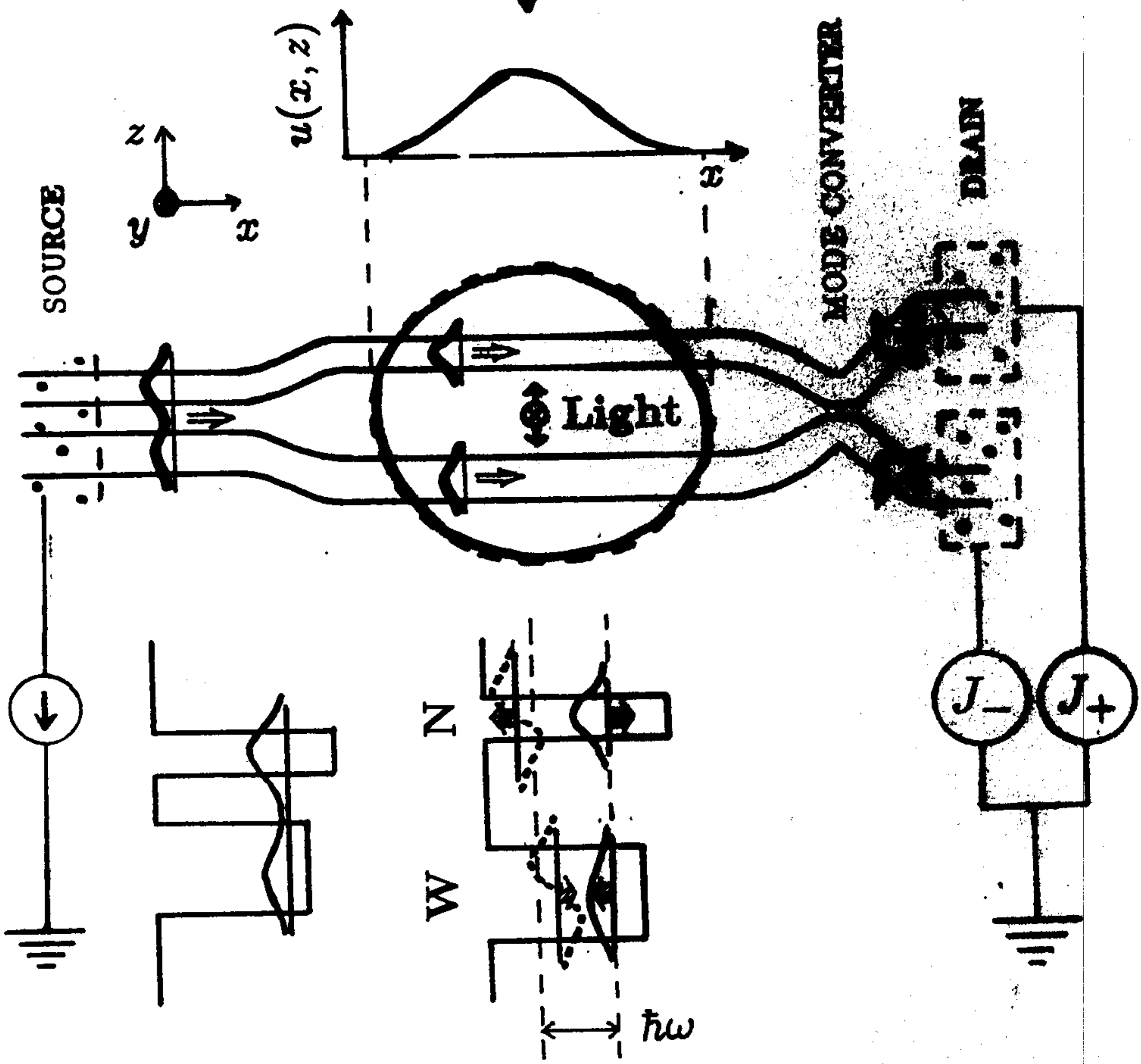


Despite $[\hat{H}_I, \hat{n}] \neq 0$, $\langle \hat{n} \rangle_{final} = \langle \hat{n} \rangle_{initial}$

A. Shimizu, Proc. 17th IQEC, May 1990
M. Brune et al., Phys. Rev. Lett. 65 976, August 1990


electron
n photons
$|b\rangle|n-1\rangle$
$|a\rangle|n\rangle$
$|\beta_{n-1}\rangle$
$|\alpha_n\rangle$
$\langle n\rangle$ is decreased!
$|b\rangle|n-1\rangle$
$|a\rangle|n\rangle$
$\langle n\rangle$ is recovered!

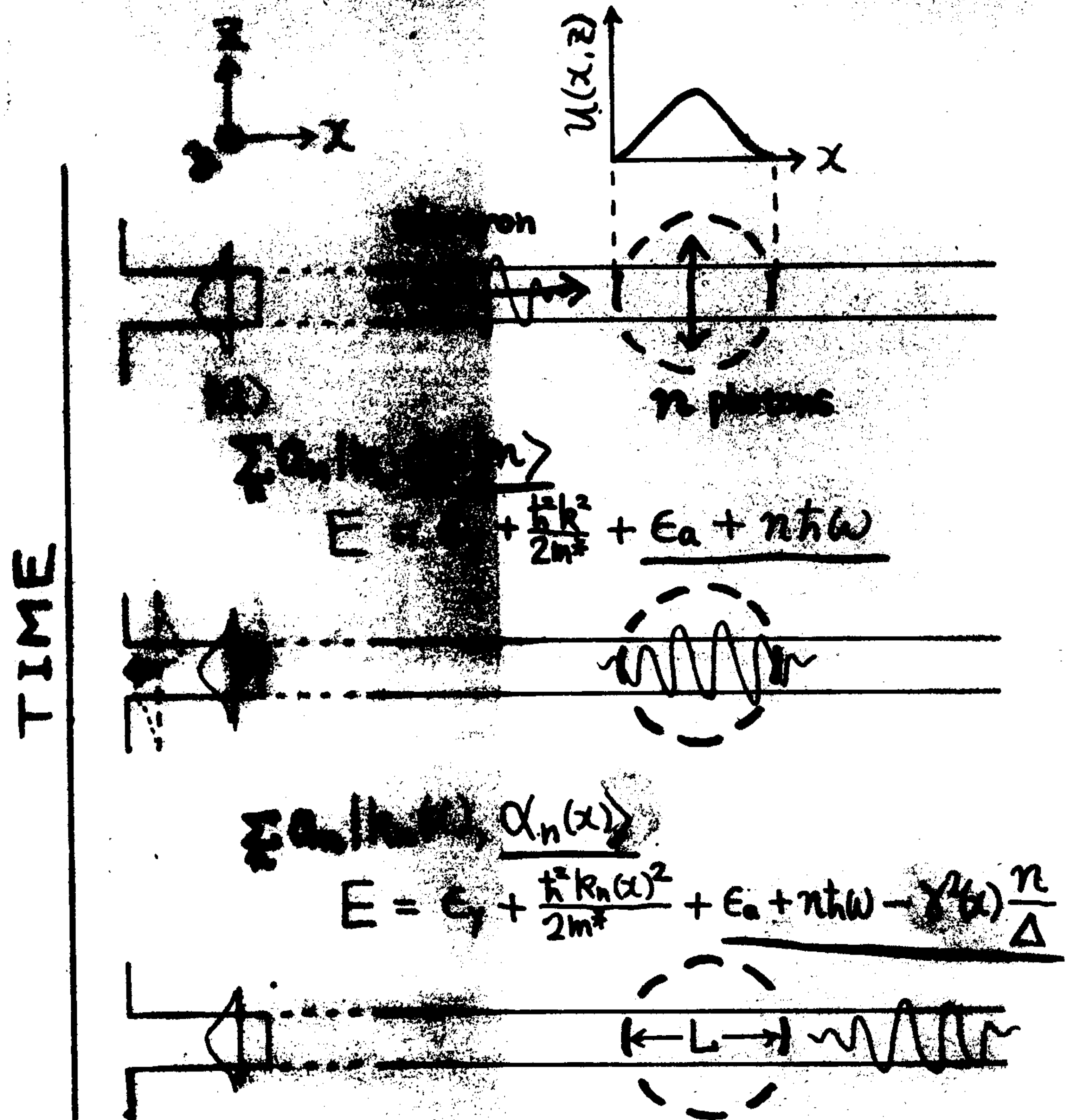
smooth profile



Deviation from adiabatic evolution

$\simeq$ degree of demolition by measurement

$\simeq 10^{-5} - 10^{-6}$



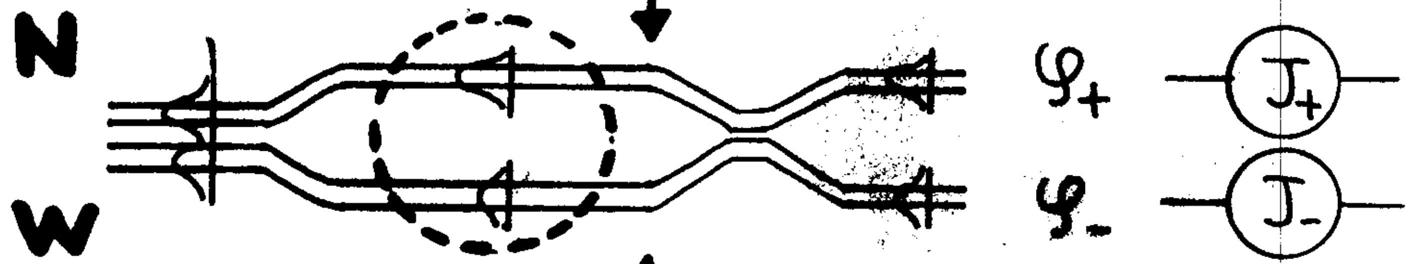
$$\sum_n a_n e^{i\theta_n} |k, a\rangle |n\rangle$$

$$\theta_n = \int_{-L/2}^{L/2} dx \cdot [k_n(x) - k] \approx \zeta\, n + \left(\text{terms independent of } n\right)$$

effective coupling constant

Photons ⊗ One el. in a Double QWR

$$\theta_n^N = \overset{>0}{\zeta_N}\, n + (\cdots)$$



$$\theta_n^W = \overset{<0}{\zeta_W}\, n + (\cdots)$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[\,|\alpha^N\rangle + |\alpha^W\rangle\,\right]\cdot \sum_n a_n |n\rangle$$

$\Downarrow$ Interaction

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}\sum_n a_n\left[e^{i\overset{>0}{\theta_n^N}}|\alpha^N\rangle + e^{i\overset{<0}{\theta_n^W}}|\alpha^W\rangle\right]\cdot|n\rangle$$

Reduced density operator

for the statistical ensemble of photon state

- $\hat{\rho}_{ph} = \sum_{n,m} a_n a_m^* |n\rangle\langle m|$: Initial state $\left(|\psi_{ph}\rangle = \sum_n a_n |n\rangle\right)$

$\hat{\rho}''_{ph} \equiv \mathrm{Tr}_{el}\, \hat{\rho}''$: Final state

\# of detected el.'s

$$= \sum_{n,m} a_n a_m^* \left[\frac{1}{2} e^{i\zeta_N(m-n)} + \frac{1}{2} e^{i\zeta_W(m-n)}\right]^N |n\rangle\langle m|$$

- **Statistical distribution of n is invariant!**

$$\mathrm{Prob}(n) = |a_n|^2 \Longrightarrow \mathrm{Prob}'(n) = |a_n|^2 \leftarrow \text{QND}$$

- **Number state is invariant!**

$$|n\rangle\langle n| \Longrightarrow |n\rangle\langle n|$$

- **Phase of coherent state is randomized!**

$$\langle \delta\phi^2 \rangle_0 \Longrightarrow \langle \delta\phi^2 \rangle_0 + \delta\phi^2_{BA}$$

Backaction noise : $\delta\phi^2_{BA} \approx N g^2 / 4$

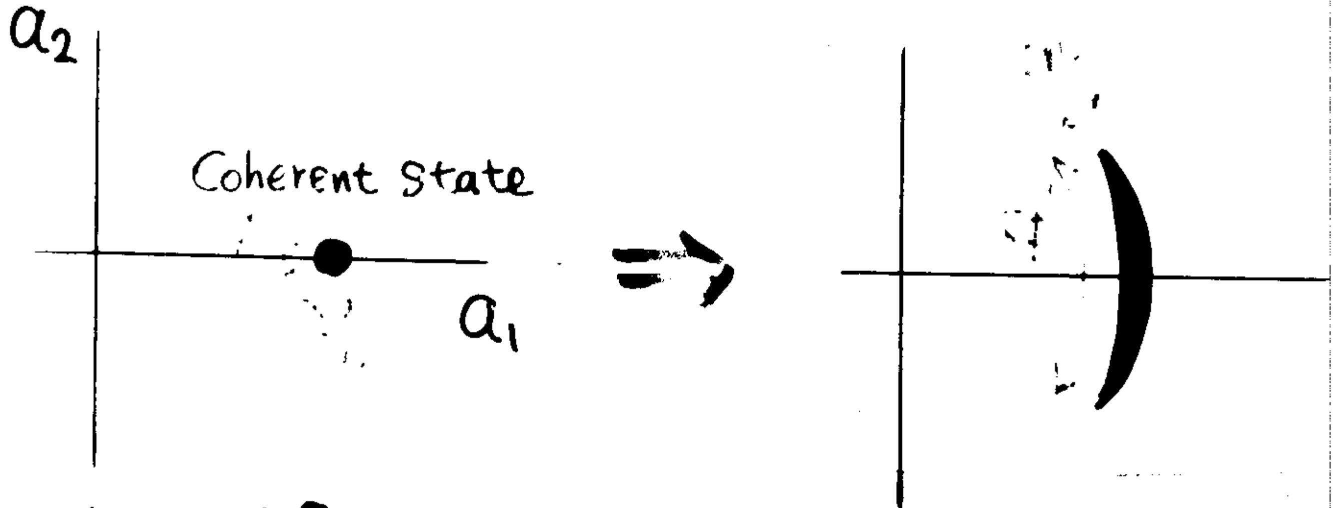
$g \equiv \zeta_N - \zeta_W$: overall effective coupling constant

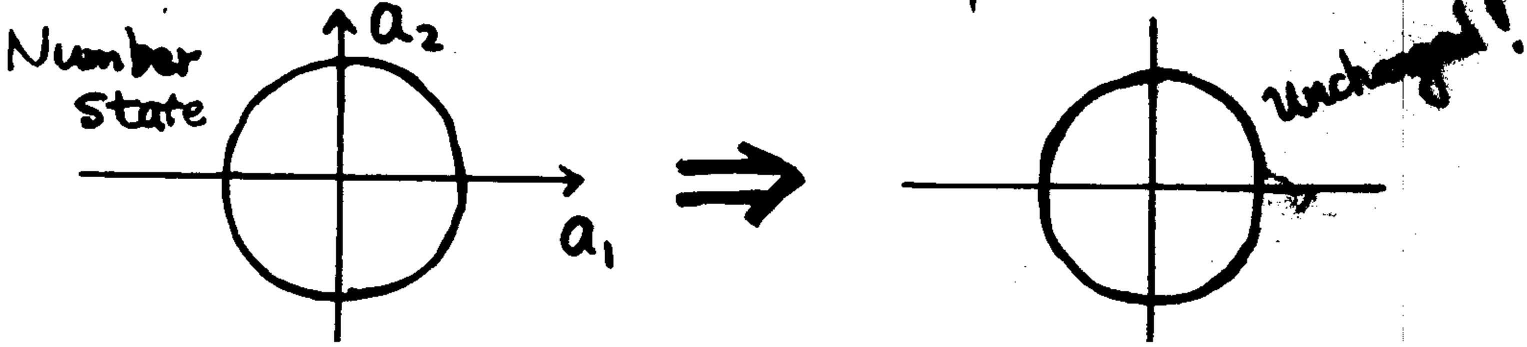
(Valid when $\langle n \rangle \gg 1$ and $g^2 N \ll 1$)

$$\begin{cases} g = \zeta_N^{>0} - \zeta_W^{<0} : \text{overall coupling const.} \\ N : \text{number of detected electrons} \end{cases}$$

Backaction : $\delta n^2_{BA} \simeq 0$ (← QND)

$$\delta\phi^2_{BA} \simeq g^2 N/4$$





MEASUREMENT ERROR

Photons hit electrons

$$\Downarrow$$

Phase shift of electron waves

$$\Downarrow$$

Modulation of Interference currents J_+, J_-

$$\Downarrow$$

Measure the currents:

$$\langle J_+\rangle - \langle J_-\rangle \propto \langle n\rangle$$

Quantum fluctuations

$\Longrightarrow$ Measurement error

$$\delta n^2_{err} = 1/g^2 N$$

Quantum Fluctuations of Fermion Current at Nonequilibrium

General theory

B. Yurke, S.L. McCall and J.R. Klauder (1986); M.F Silverman (1987); M. Kitagawa and M. Ueda (1991)

Mesoscopic systems (elastic) Settled

V. A. Khlus (1987); G. B. Lesovik (1989); B. Yurke and G. P. Kochanski (1990); M. Büttiker (1990); C. W. Beenakker and H. van Houten (1991); R. Landauer and T. Martin (1991)

Fundamental limits of quantum interference devices Settled

A. Shimizu and H. Sakaki (1991)

Mesoscopic systems (dephasing and dissipation) Not settled

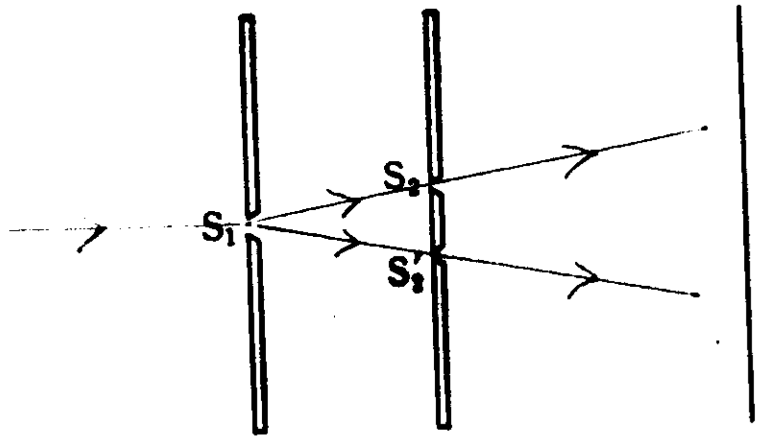
C.W.J. Beenakker and M. Büttiker (1992); A. Shimizu and M. Ueda (1992); M. Ueda and A. Shimizu (1993)

Experiment Not settled

Y.P. Li, D.C. Tsui, J.J. Hermans, J.A. Simmons and G. Weimann (1990).

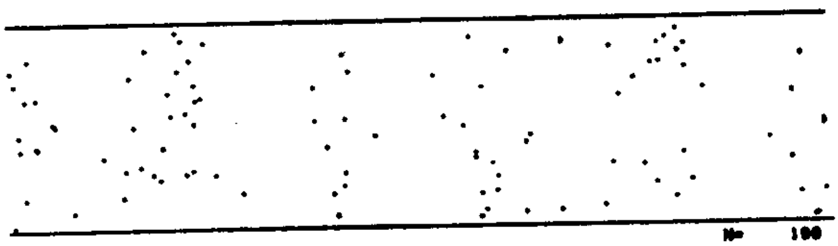
To measure the **phase** of an electron wavefunction, we need **many** electrons in the same state!

(See the beautiful experiment by A. Tononmura!
A. Tonomura, Physics Today, April 1990)

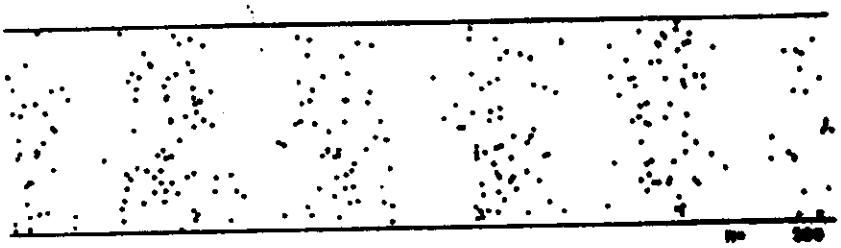


N : the number of electrons detected during the measureme

N = 100

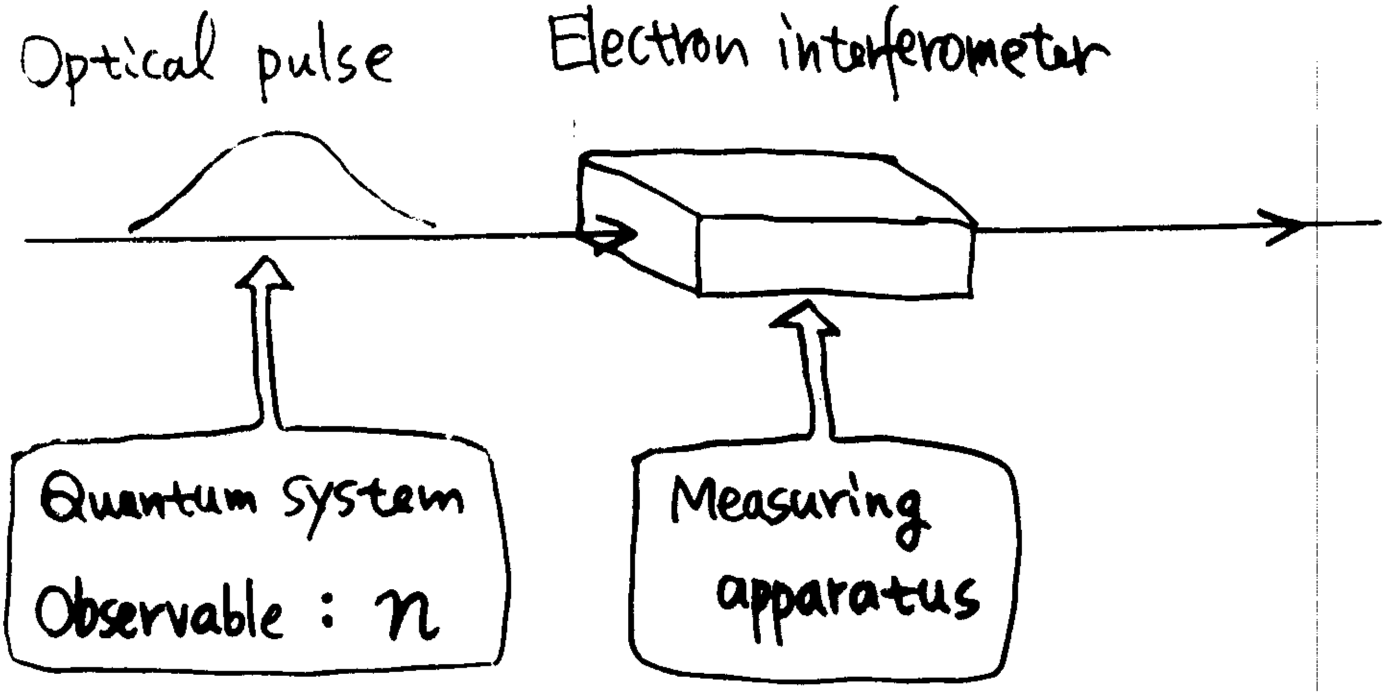


N = 300



N = 1500

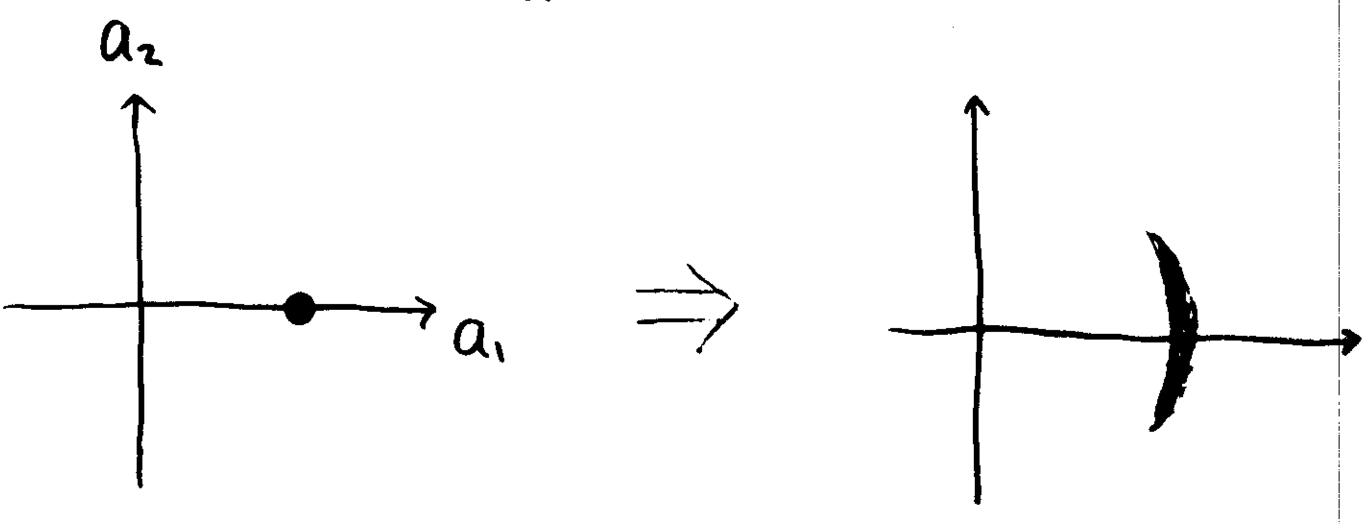
After H. Ezawa in 量子力学と新技術 (Baifukan, Tokyo, 1987)



Measurement error : $\delta n_{err}^2 \simeq \dfrac{1}{g^2 N}$

Backaction : $\delta n_{BA}^2 \simeq 0 \quad (\leftarrow \text{QND})$

$$\delta \phi_{BA}^2 \simeq g^2 N/4$$



Uncertainty product : $\delta n_{err}^2 \cdot \delta \phi_{BA}^2 \simeq \dfrac{1}{4}$

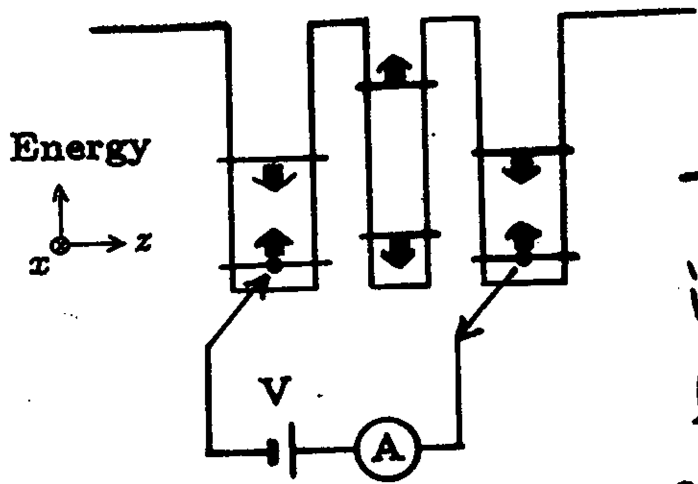
(<u>c.f.</u> General requirement is $\delta n_{err}^2 \cdot \delta \phi_{BA}^2 \gtrsim \dfrac{1}{4}$)

CONCLUDING REMARKS

Possible Uses of Other Interferometers

Ex. 1. Resonant Tunneling Diode

A. Shimizu, Proc. 17th IQEC '90

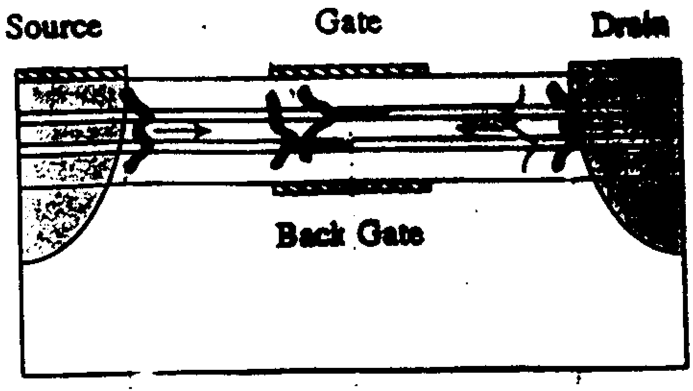


Tunneling current is modulated by light beam, without changing photon number!

Ex. 2. Field-Controlled Interferometer

Theoretical Proposal : Okuda et al., APL 57 ('90) 2231, JAP 74 ('93)

Experiment : Okuda et al., PR B47 ('93) 4103, APL 63 ('93) 3309



 is constructed in **straight** double quantum wire structure!

Part III

Photon-energy dissipation caused by an external electric circuit in "virtual" photo-excitation processes

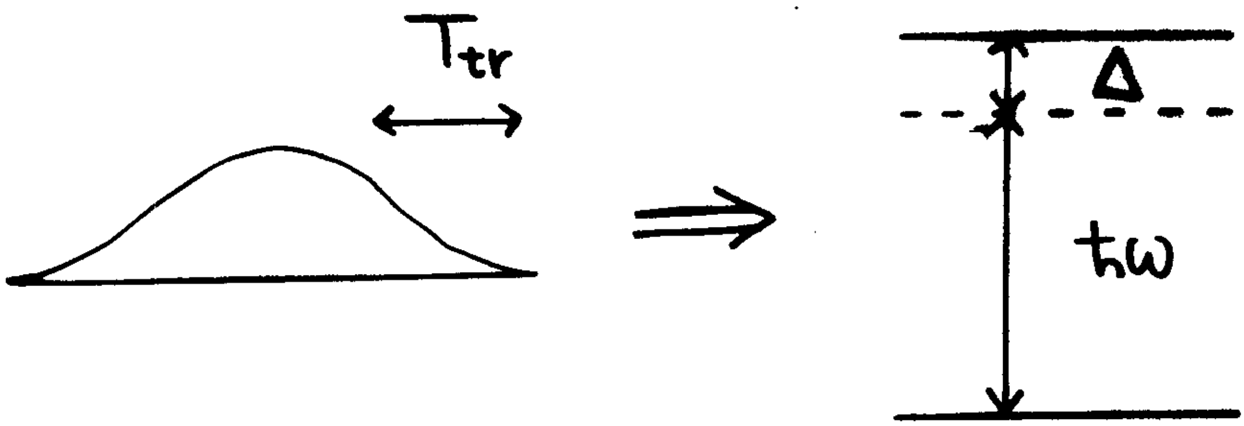
Akira Shimizu

Institute of Physics, Univ. Tokyo, Komaba, Tokyo, Japan

Masamichi Yamanishi

Department of Physical Electronics, Hiroshima Univ., Japan

(Phys. Rev. Lett. 72 (1994) 3343)



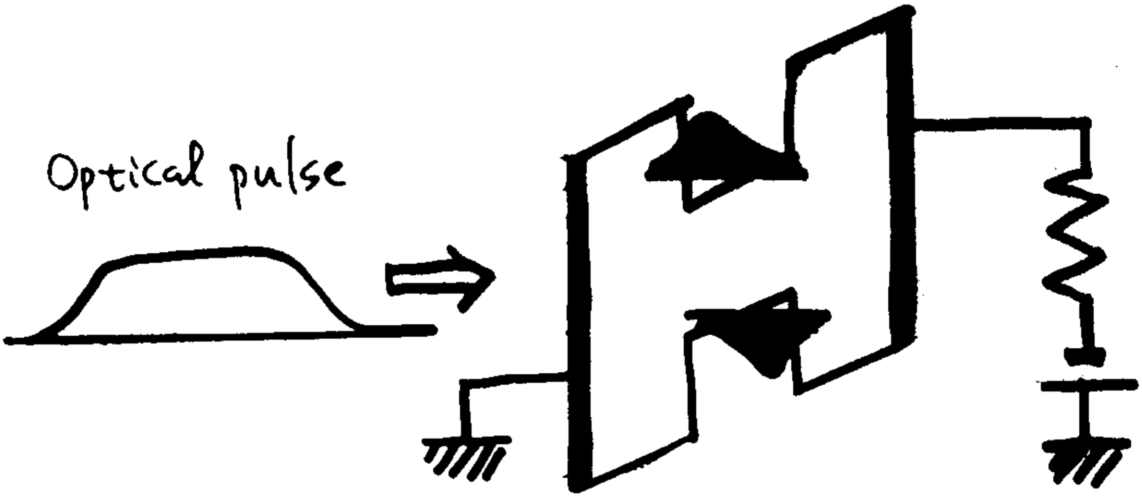
"Virtual" if

$$\left(\frac{T_{tr}}{\hbar}\right)^2 \gg \left(\frac{\mu \mathcal{E}}{\Delta^2}\right)^2$$

← Adiabatic Condition!

Generation of ultrashort electrical pulses from an electrically-biased QWS

M. Yamanishi, PRL 59 (1987) 1014; D.S. Chemla, D.A.B. Miller, S. Schmitt-Rink, PRL 59 (1987) 1018.



$\hbar\omega$ < absorption edge

$\longrightarrow$ virtual excitation

$\longrightarrow$ ultrafast response

Biased multiple QWS

$\longrightarrow$ large $\chi^{(2)}(0; -\omega, \omega)$

$\longrightarrow$ high generation efficiency

QUESTIONS

(i) What is the state of the optical pulse after it passes through the QWS. What is the photon energy and photon number?

(ii) What role is played by the external electric? circuit

(iii) What supplies the energy to the electrical pulse — an external battery or the optical field?

(iv) Is it possible to perform a QND measurement by monitoring the generated electrical pulse?

Excitons are strongly deformed by F_0

$\longrightarrow$ large *static* dipole moment; $l = 10^{1-2}$ Å

- Describe the exciton dynamics *in terms of such deformed states.*

- Consider the lowest-exciton state only.
(Multi-level effects do not alter the main conclusions.)

$$H = \varepsilon_x a^\dagger a - \mu(a^\dagger + a)\underbrace{\mathcal{E}\cos\omega t}_{\text{optical field}} - l(F_P + F_1)a^\dagger a$$

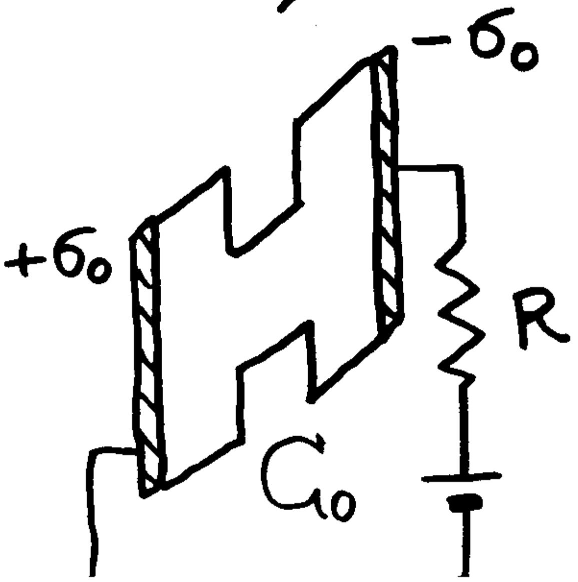
$$F_P = -l\langle a^\dagger a\rangle/\epsilon_0$$

$$F_1 = \sigma_1/\epsilon$$

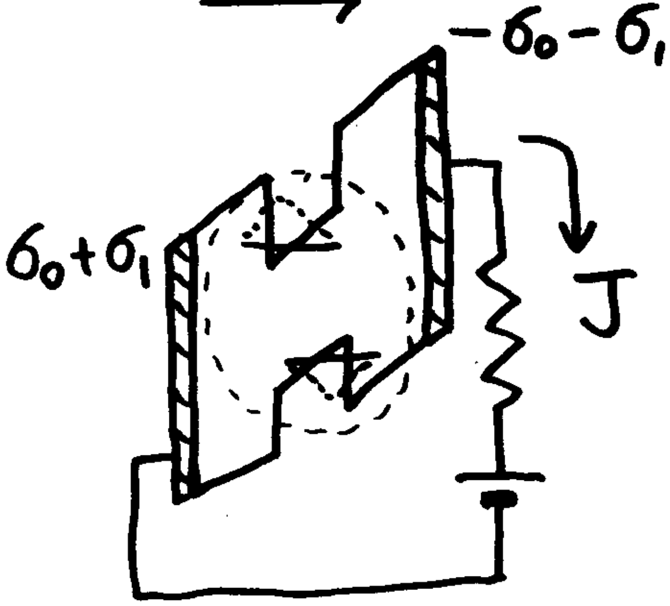
$$\frac{d\sigma_1}{dt} = -\frac{\sigma_1}{C_0 R} - \kappa\frac{F_P}{RL}$$

$$\begin{cases} \kappa = \dfrac{\text{Well thickness}}{\text{Total thickness}} \\ L = \text{interaction length} \end{cases}$$

$F_0 = \sigma_0/\epsilon$ $\longrightarrow$



$F = F_0 + F_P + F_1$ $\longrightarrow$



Role of the external battery

F_0 determines a, $a^\dagger$, μ, and l.

But, not appeared explicitly!

$\longrightarrow$ External battery supplies NO net energy.

$\longrightarrow$ RJ^2 must be supplied by the **optical** field.

$\longrightarrow$ Role of the **battery** (and F_0) **is just** to produce large $\chi^{(2)}$.

We calculate ...

- evolution of the optical field
- energy flow

to $O(\mathcal{E}^2)$.

(2nd-order effects are found to be essential.)

Concerning these quantities,

the microscopic model ← Excitons induce nonlinear effects

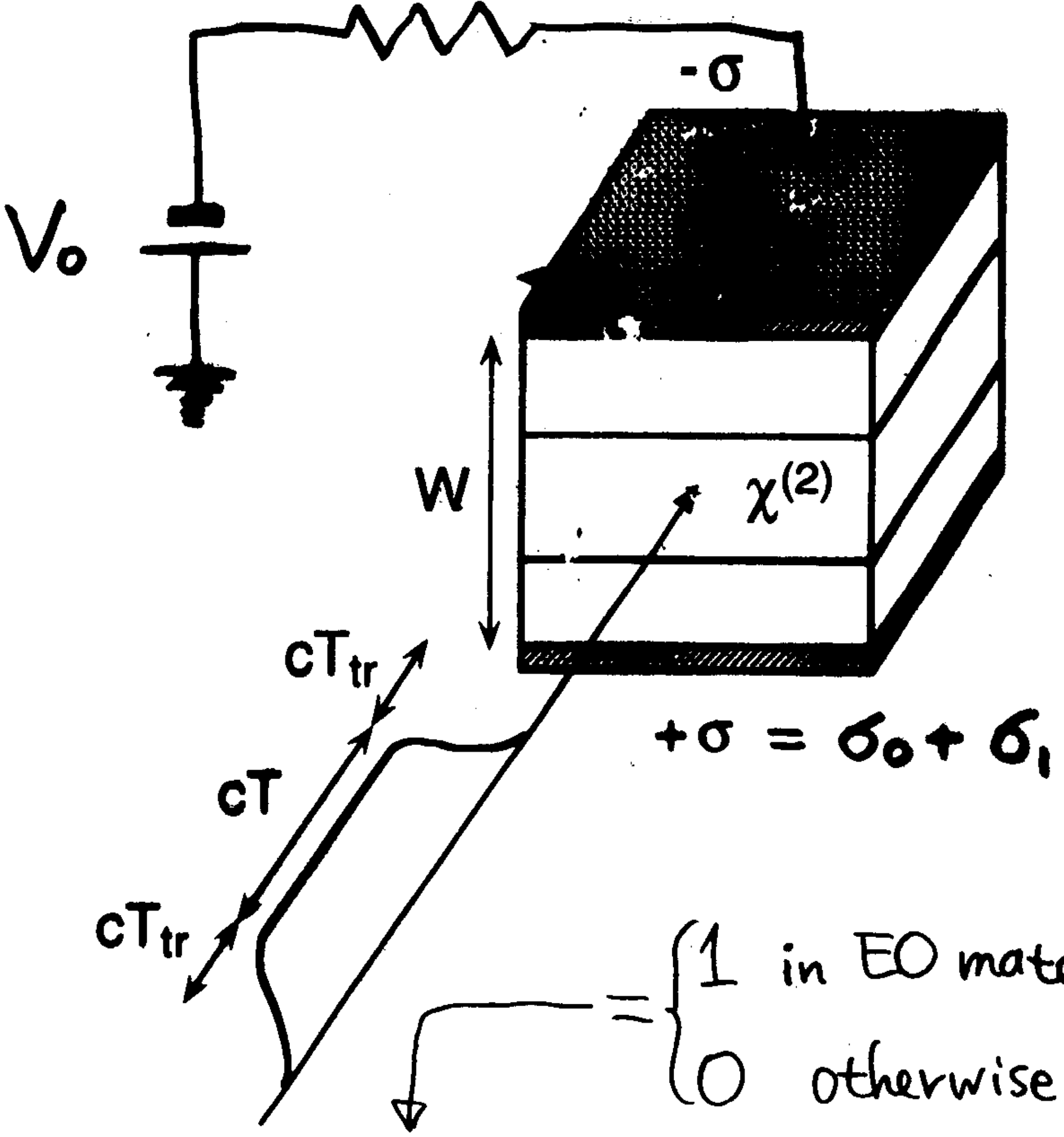
gives the same results as

a phenomenological model. ← $\chi^{(2)}$ is a given parameter

⟶ applicable to any transparent EO materials

including the biased QWS.

> Hereafter present the results in the language of the phenomenological model.



$$\Theta = \begin{cases} 1 & \text{in EO material} \\ 0 & \text{otherwise} \end{cases}$$

$$F = F_0 + F_p \Theta + F_1$$

$$F_0 = V_0/W = \sigma_0/\epsilon$$

$$F_p = -\frac{\epsilon_0}{\epsilon}\chi^{(2)}(0;-\omega,\omega)\mathcal{E}^2 \; : \text{optical rectification}$$

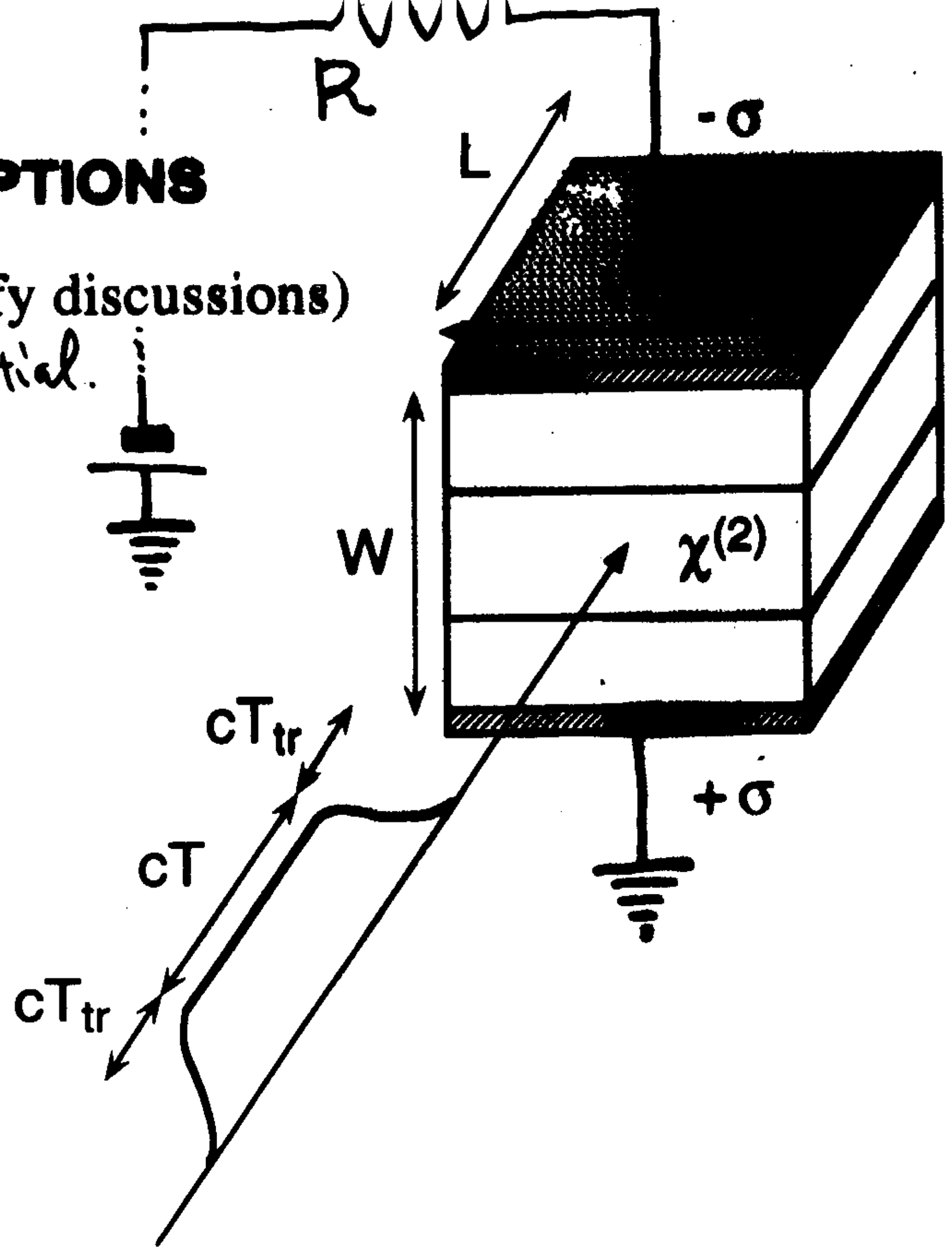
$$F_1 = \sigma_1/\epsilon$$

values at $F_0 \neq 0$

$$\delta n = \frac{1}{2n^3}\chi^{(2)}(\omega;\omega,0)(F_p + F_1) \; : \text{electro-optic effect}$$

ASSUMPTIONS

(To simplify discussions)
NOT essential.



1. Cross section of light beam
   = cross section of sample

2. $T_{tr} << C_0 R$ → σ does not change during T_{tr}

3. $T_{tr} << T$

4. $L << cT/n$ → $\mathcal{E} \simeq$ constant in the sample.

(C_0 : capacitance in the absence of light field)

Light intensity:

$$I = \epsilon_0 c n \mathcal{E}^2/2$$

Induced DC field:

$$F_P = -(\epsilon_0/\epsilon)\chi^{(2)}\mathcal{E}^2$$

Current driven by F_P:

$$J = \begin{cases} \dfrac{\kappa W}{R}|F_P| e^{\frac{-t}{C_0 R}} \\ \qquad (0 \le t \le T), \\ \dfrac{\kappa W}{R}|F_P|(1 - e^{\frac{-T}{C_0 R}})e^{\frac{T-t}{C_0 R}} \\ \qquad (T < t) \end{cases}$$

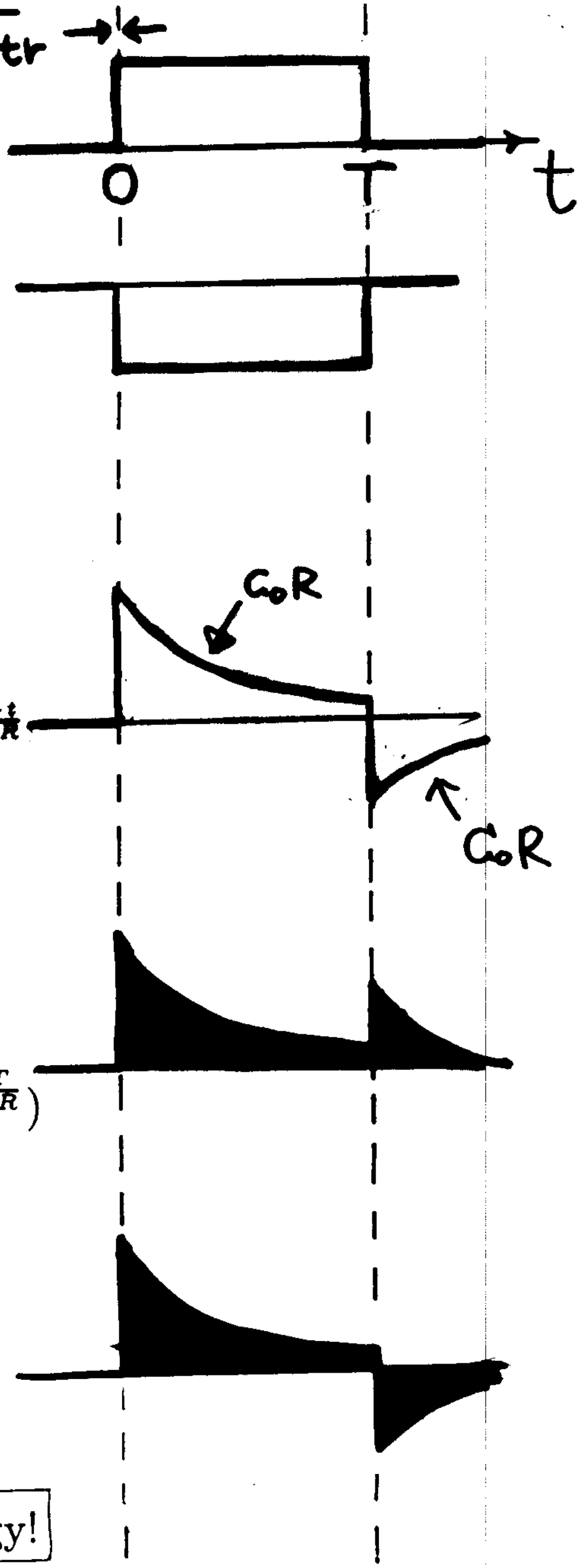
Joule heat generated in R:

$$U_R = \int_{-\infty}^{\infty} R J^2 dt$$
$$= \frac{(\kappa W L \epsilon_0 \chi^{(2)} \mathcal{E}^2)^2}{C_0}(1 - e^{\frac{-T}{C_0 R}})$$

Work done by the battery:

$$U_{V_0} = \int_{-\infty}^{\infty} V_0 J dt$$
$$= V_0 W L[\sigma_1(\infty) - \sigma_1(0)]$$
$$= 0$$

Battery supplies no net energy!



$J \rightarrow$ **Change of** $\sigma = \sigma_0 + \sigma_1$**:**

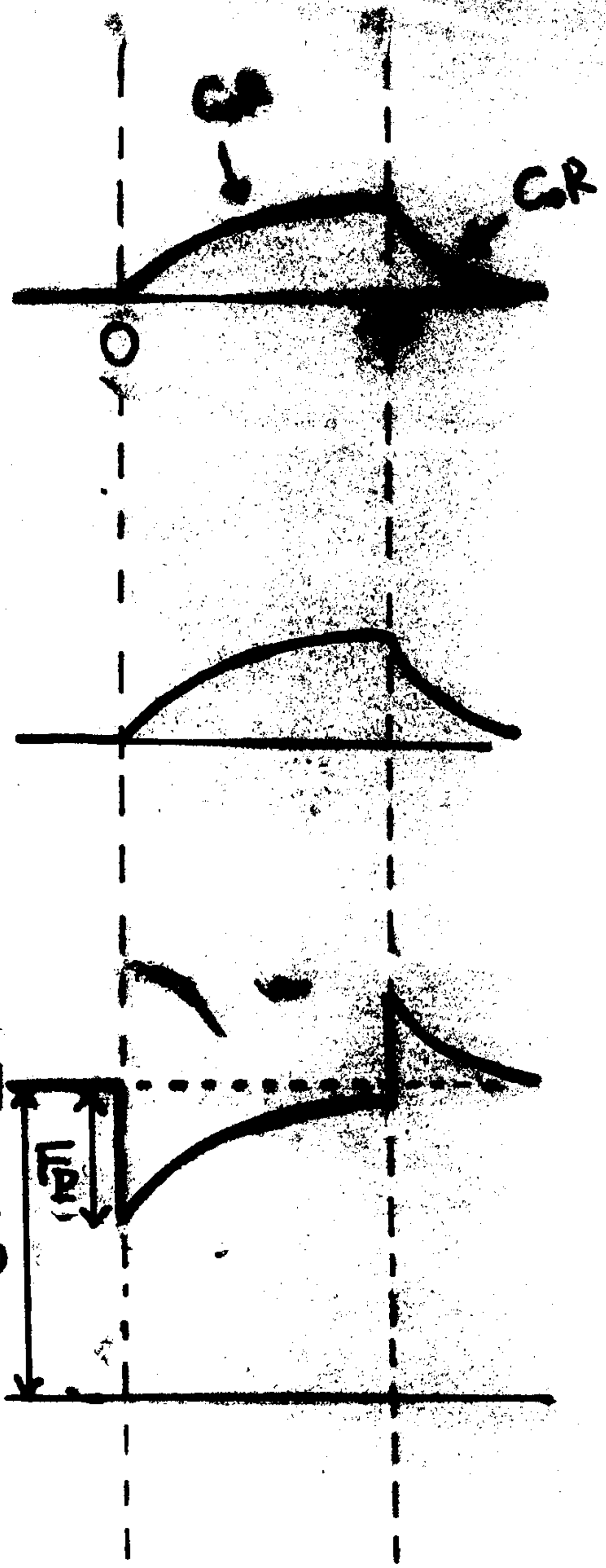
$$\sigma_1 = \begin{cases} \kappa\epsilon|F_P|(1 - e^{\frac{-t}{C_0R}}) \\ \qquad (0 \leq t \leq T), \\ \kappa\epsilon|F_P|(1 - e^{\frac{-T}{C_0R}})e^{\frac{T-t}{C_0R}} \\ \qquad (T < t) \end{cases}$$

$\sigma_1 \rightarrow$ **Canceling field:**

$$F_1 = \sigma_1/\epsilon$$
$$= -\kappa F_P(1 - e^{\frac{-t}{C_0R}})$$
$$(0 \leq t \leq T)$$

DC field in EO material:

$$F = F_0 + F_P + F_1$$
$$= F_0 + F_P[1 - \kappa(1 - e^{\frac{-t}{C_0R}})]$$
$$(0 \leq t \leq T)$$



Change of refractive index:

$$\delta n = \chi^{(2)}(\omega;\omega,0)(F_2 + F_1)/2n$$
$$= -\chi^{(2)}(\omega;\omega,0)\chi^{(2)}(0;-\omega,\omega)$$
$$\times \frac{\epsilon_0}{2n\epsilon}\mathcal{E}^2[1-\kappa(1-e^{\frac{-t}{C_0R}})]$$
$$(0 \le t \le T)$$

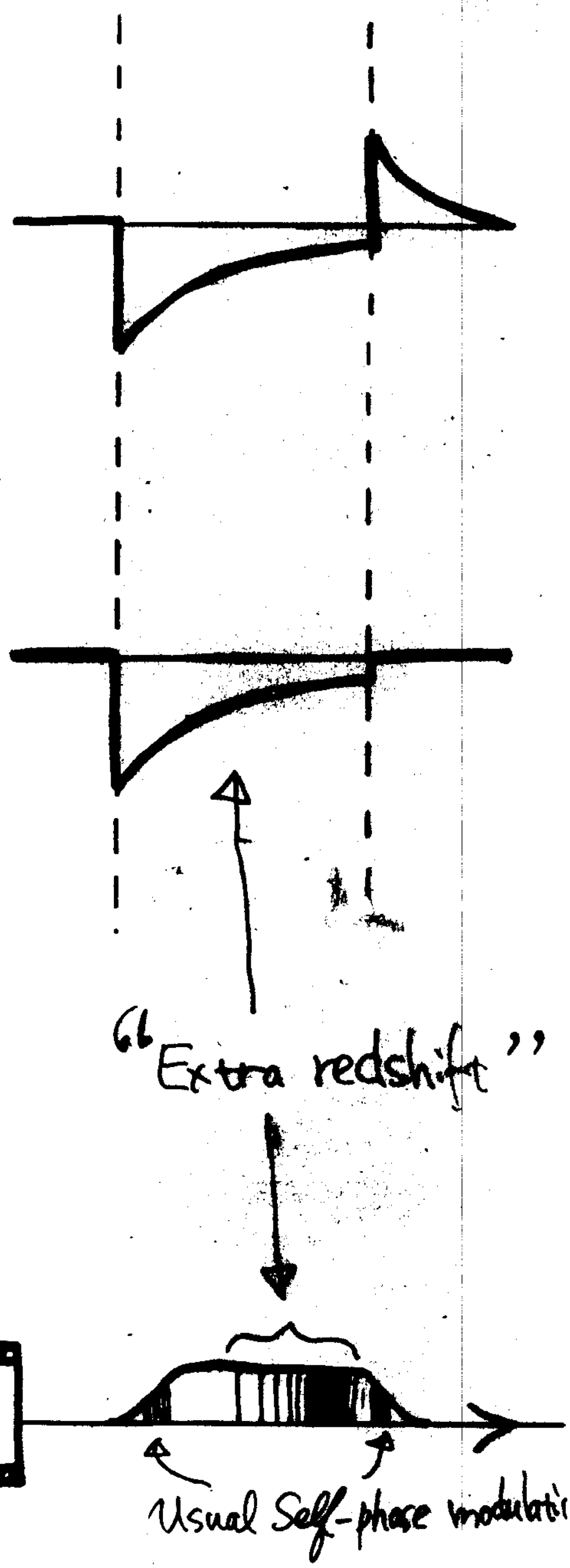
Modulation of light frequency:

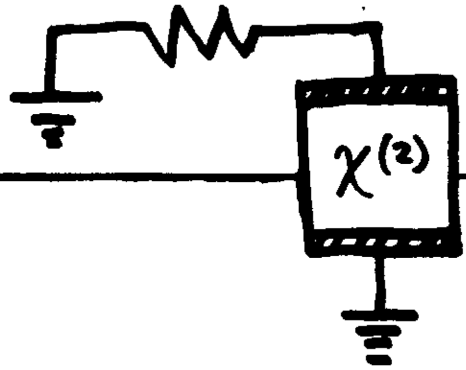
When $L \ll C_0Rc/n$,

$$\delta\omega = -\frac{\partial}{\partial t}\frac{2\pi L\kappa\delta n}{\lambda_0}$$
$$= -\frac{2\epsilon_0\omega\kappa^2|\chi^{(2)}|^2\mathcal{E}^2 L}{n\epsilon c C_0 R}e^{-t/C_0R}$$

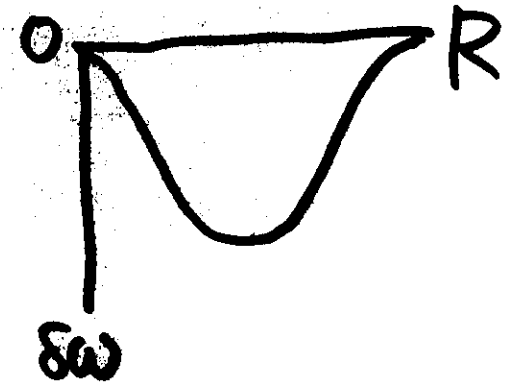
where

$$\chi^{(2)} \equiv \chi^{(2)}(0;-\omega,\omega)$$
$$= \chi^{(2)}(\omega;\omega,0)/4$$

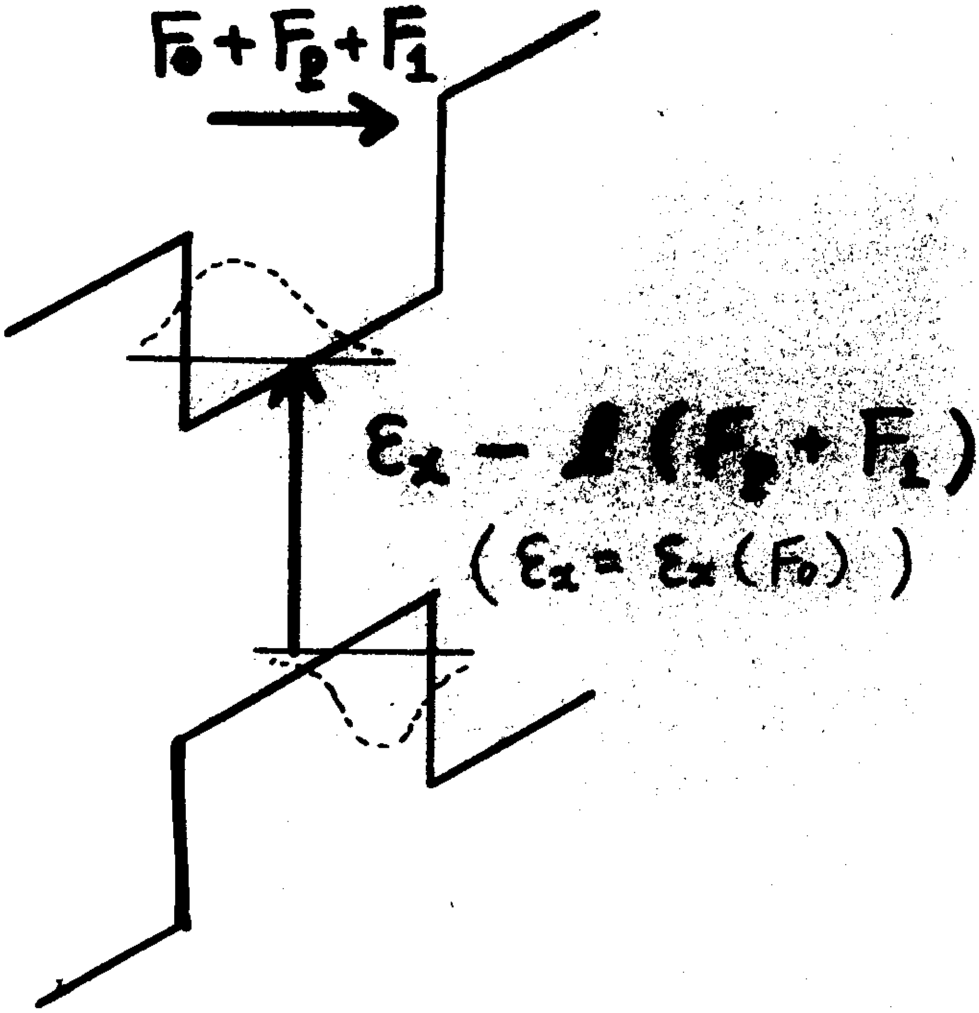


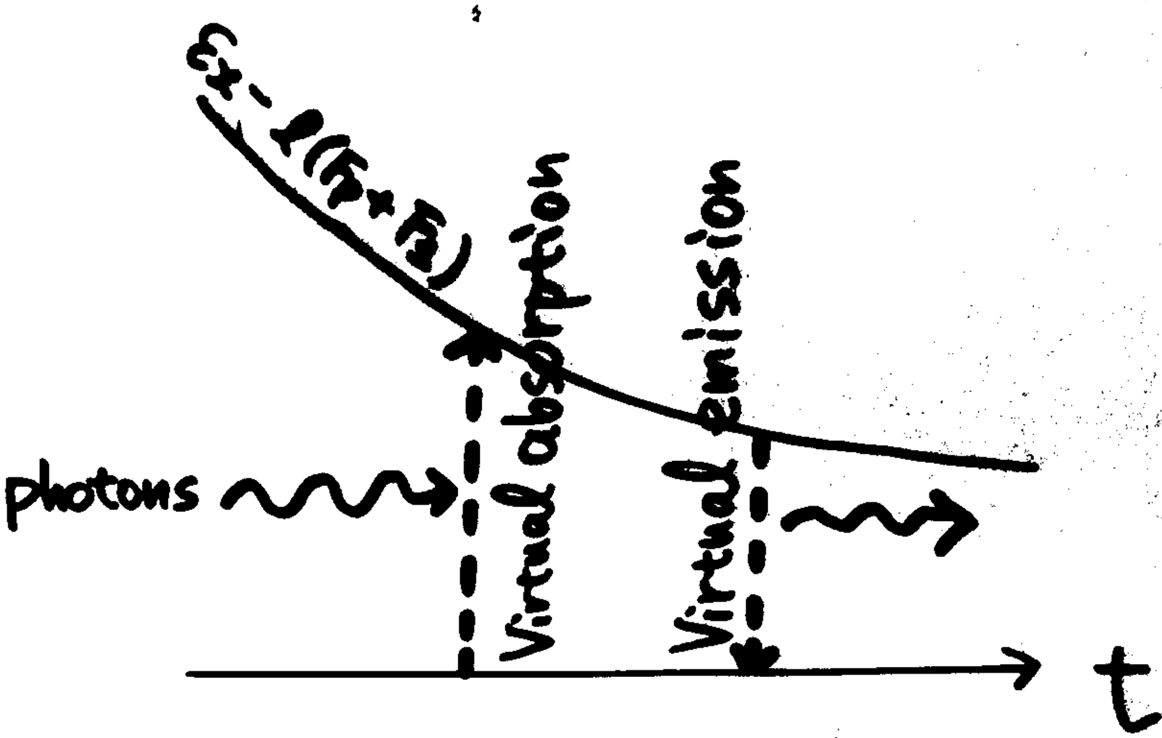


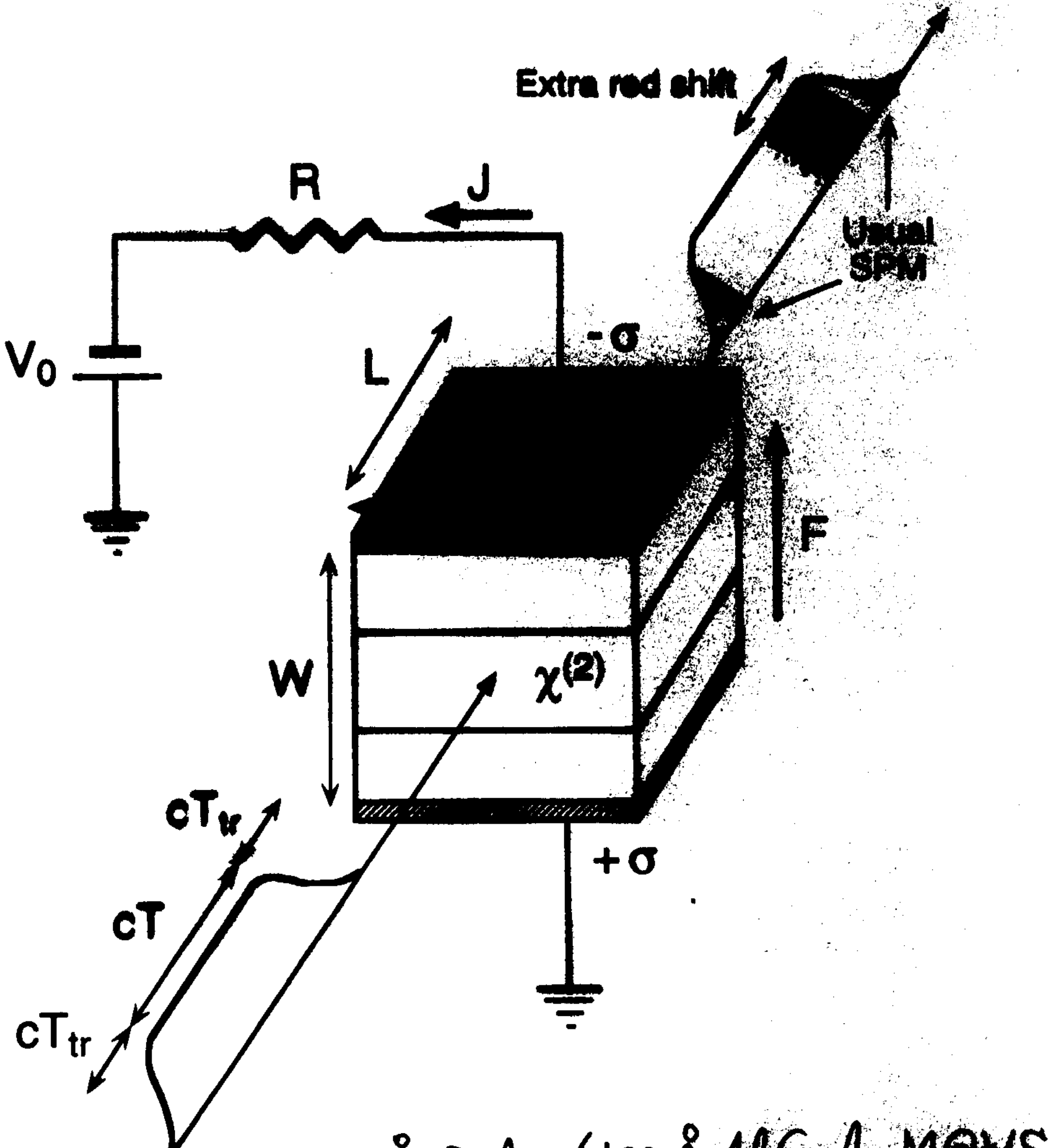
Totally different from ~~the~~ usual self-phase modulation!

	Usual SPM	Extra Redshift
R dependence	NO	
Total energy	Conserved	Lost (as shown later.)
Delay	$\simeq$ instantaneous	$\sim C_0 R$
Whose property?	EO material alone.	Coupled system of the EO material and the external circuit

Microscopic interpretation







ex. 100Å GaAs / 100Å AlGaAs MQWS

$\delta\omega \sim 2\pi \times 10^2 L[\mu m]$ MHz

when

$I \sim 10^2$ MW/cm^2, $F_0 \sim 10^2$ kV/cm

$T \sim C_0 R \sim 1$ ps, $\Delta = 10$ meV

Energy flow

Loss of the optical energy due to the extra redshift:

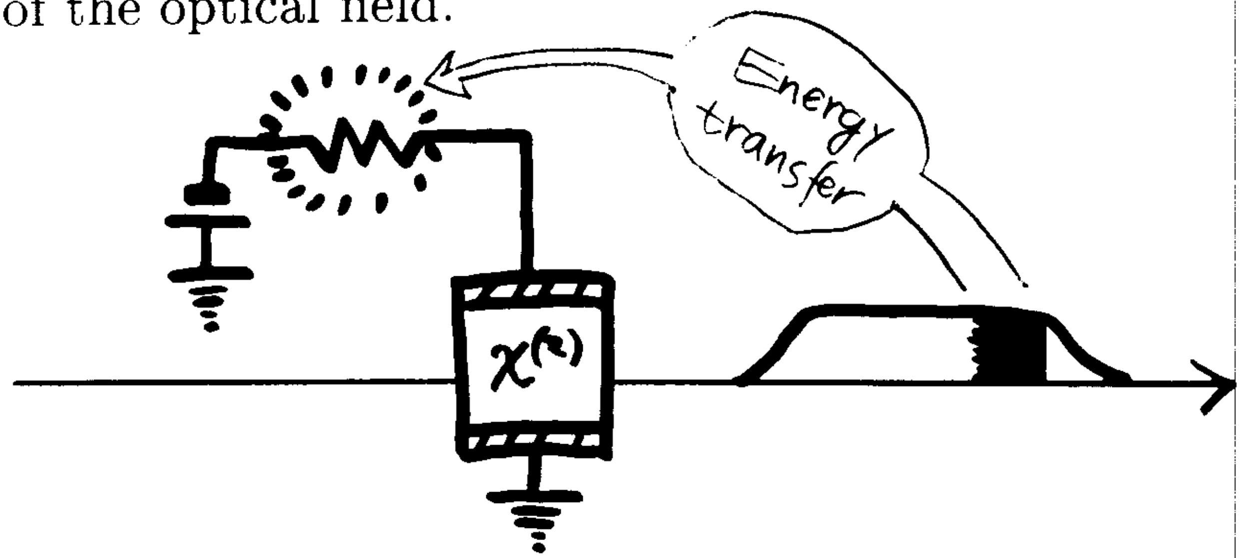
$$U_{ERS} = \int_0^T |W^2 \delta I|\, dt, \quad \left(\frac{\delta I}{I} = \frac{\delta \omega}{\omega}\right)$$

$$= \frac{W^2 I L \kappa}{c}[\delta n(T) - \delta n(0)]$$

$$= \frac{(\kappa W \epsilon_0 \chi^{(2)} \mathcal{E}^2)^2 L}{\epsilon}\left(1 - e^{-\frac{T}{\sigma_0 \kappa}}\right)$$

$$= U_R$$

- Joule energy is supplied only by the extra redshift of the optical field.



- Photon number is conserved.

$\longrightarrow$ Our photon-energy dissipation cannot be described as a simple dephasing process!

SUMMARY of Part III

Considered ...

- Electrical-pulse generation in the "virtual excitation" regime.
- The electronic system is any [illegible] including a QWS biased by a dc electric field.
- The energy transfer is analyzed when the electronic system is coupled to an external circuit.

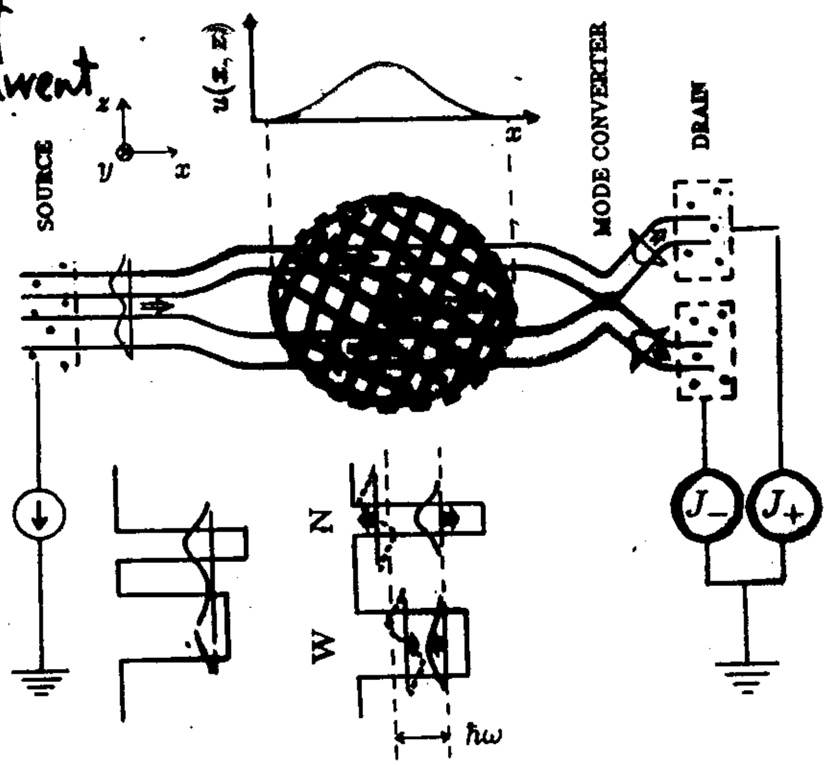
Found ...

- The photon *frequency* is subject to an extra redshift in addition to the usual self-phase modulation.
- The photon *number* is conserved.
- The extra redshift approaches zero in both limits of zero and infinite impedance of the circuit.
- The external battery supplies *no net energy*.
- The Joule energy consumed in the external circuit is supplied only from the extra redshift.

Probing "virtually excited" electronic systems with electric circuits

- Modulation of interference current

M. [redacted] ('88)
A. Shimizu ('90)



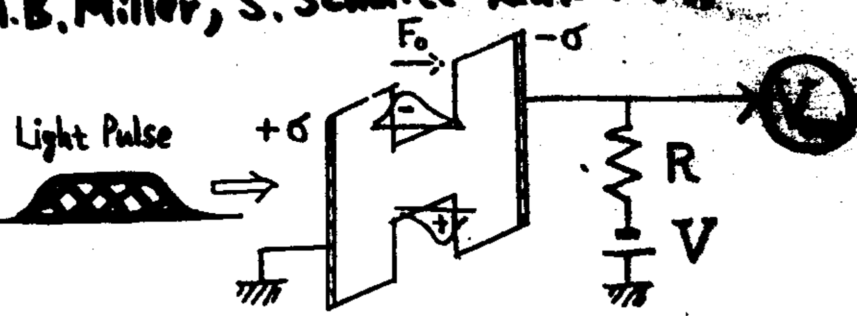
Light
↓
Optical Stark Shift
↓
Phase shift
↓
Interference Currents

Both n_{ph} and ω are conserved

⟶ Quantum non-demolition photodetector A. Shimizu ('9

- Generation of an electric pulse

M. Yamanishi ('87)
D.S. Chemla, D.A.B. Miller, S. Schmitt-Rink ('87)



Light
↓
Virtual Charge
↓
DC electric pulse

n_{ph} is conserved, but ω is **not**.

⟶ Quasi QND? [redacted]
(need more justification)

In the "virtual" excitation processes, the photon energy will or will not be conserved depending on the structure of electronic systems *and* the external circuit, although the circuit does *not* interact with the optical field directly.