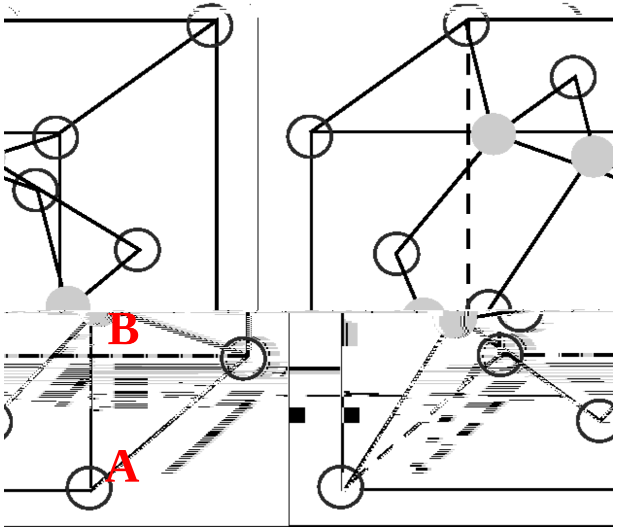
Institute of Semiconductors CAS

1960

1

T_d GaAs InP

Pockels



2

e_{xy} [001] E_z

GaAs

Ga As

(110) $(1\underline{1}0)$

Ga-As

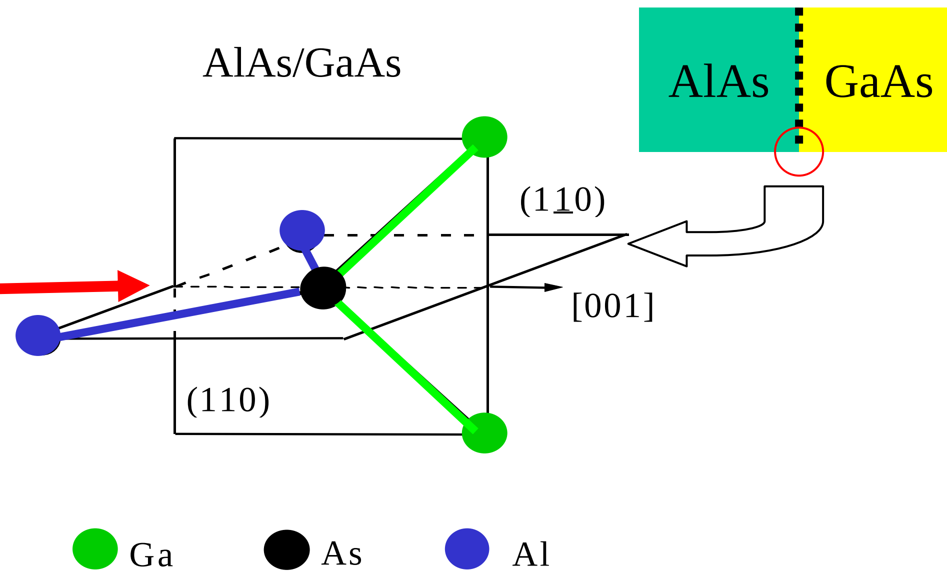
$\mathbf{C_{2v}}$

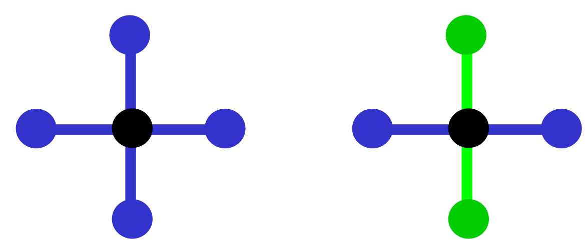
3

Ga-As (110)

Al-As (1$\underline{1}$0)

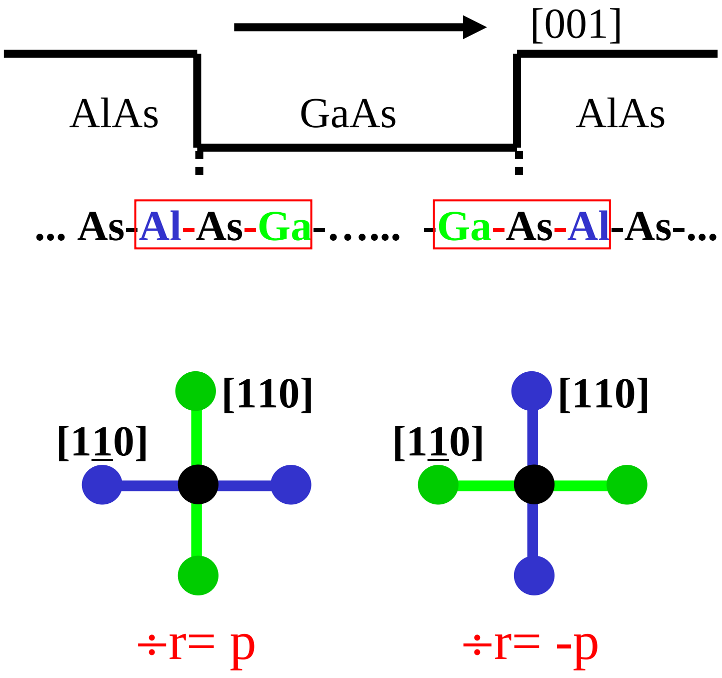
$\mathbf{C_{2v}}$





÷r=0   ÷r∏0

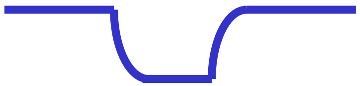
[110] **$[1\underline{1}0]$**



C_{2V}

♥

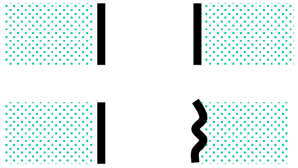
☑ InGaAs/GaAs



☑ GaAs/AlGaAs

[110]

$[1\underline{1}0]$



☑ InGaAs/InP

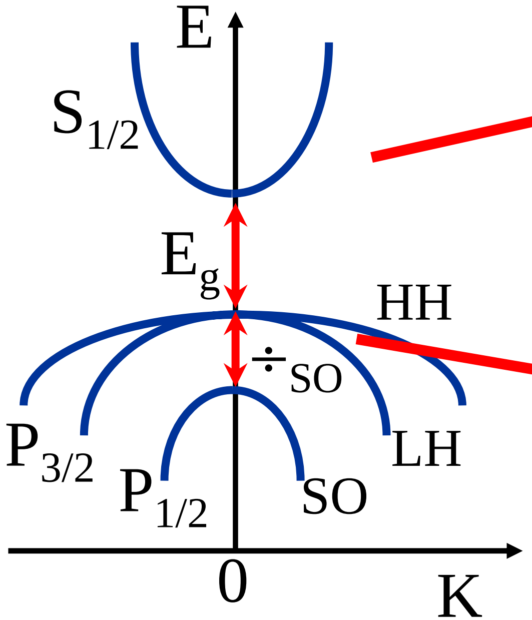
☑

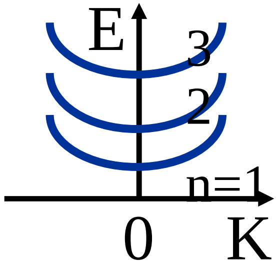
1 BIA: bulk inversion asymmetry T_d

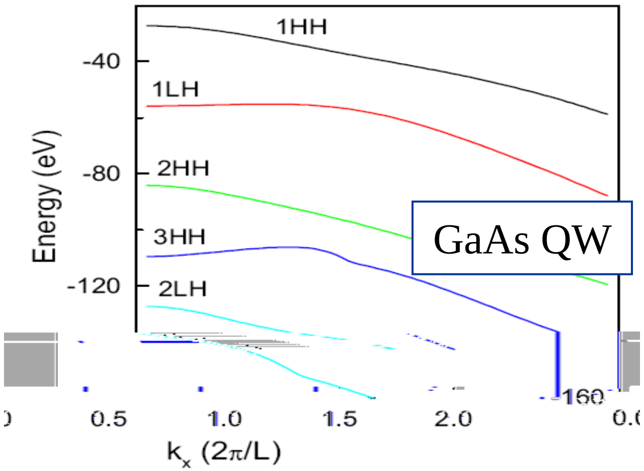
2 FIA strain and electric field C_{2V}

3 SIA: structural inversion asymmetry C_{2V}

GaAs







1
2

1
2
3 K 0

C_{2v}

E_z e_{xy}

T_d

Γ_1: S $[1]$;

Γ_2: T_2 $[x l_x + y l_y + z l_z]$;

; Γ_3: (U, V) $[\sqrt{3}(x^2 - y^2), 2z^2 - x^2 - y^2]$

Γ_4: (P, Q, R) $[l_x, l_y, l_z]$; ω3#J Γ

Γ_5: (X, Y, Z) $[x, y, z]$; k, E( ) , $[e_{yz}, e_{zx}, e_{xy}]$

$[\{j_y j_z\}, \{j_z j_x\}, \{j_x j_y\}]$

$\{j_x j_y\} = (j_x j_y + j_y j_x)/2$

T_d

TABLE I. Multiplication table for the components of the irreducible representations of T_d group. The components are defined in Eq. (4.1). This table is equivalent to that of coupling coefficients in G. F. Koster, J. O. Dimmock, R. G. Wheeler, and H. Statz, *Properties of Thirty-two Point Groups* (M.I.T., Cambridge, 1963).

S	SS'	TT'	$UU'+VV'$		$PP'+QQ'+RR'$		$XX'+YY'+ZZ'$	
T	ST'		$UV'-VU'$			$PX'+QY'+RZ'$		
U	SU'	$-TV'$	$UV'+VU'$		$\sqrt{3}(PP'-QQ')$	$2RZ'-PX'-QY'$	$\sqrt{3}(XX'-YY')$	
V	SV'	TU'	$UU'-VV'$		$2RR'-PP'-QQ'$	$\sqrt{3}(QY'-PX')$	$2ZZ'-XX'-YY'$	
P	SP'	TX'	$(\sqrt{3}U-V)P'$	$-(\sqrt{3}V+U)X'$	$QR'-RQ'$	$QZ'+RY'$	$YZ'-ZY'$	
Q	SQ'	TY'	$-(\sqrt{3}U+V)Q'$	$(\sqrt{3}V-U)Y'$	$RP'-PR'$	$RX'+PZ'$	$ZX'-XZ'$	
R	SR'	TZ'	$2VR'$	$2UZ'$	$PQ'-QP'$	$PY'+QX'$	$XY'-YX'$	
X	SX'	TP'	$-(\sqrt{3}V+U)P'$	$(\sqrt{3}U-V)X'$	$QR'+RQ'$	$QZ'-RY'$	$YZ'+ZY'$	
Z'	Y	$-SY'$	TQ'	$(\sqrt{3}V-U)Q'$	$-(\sqrt{3}U+V)Y'$	$RP'+PR'$	$RX'-PZ'$	$ZX'+X$
X'	Z	SZ'	TR'	$2UR'$	$2VZ'$	$PQ'+QP'$	$PY'-QX'$	$XY'+Y$

R R'

ρ | $(k_y^2-k_z^2)k_x$
$(k_z^2-k_x^2)k_y$
$(k_x^2-k_y^2)k_z$

$\{j_y j_z\}$
$\{j_z j_x\}$
$\{j_x j_y\}$

$\{\omega_y \omega_z\}$
$\{\omega_z \omega_x\}$
$\{\omega_x \omega_y\}$

$H=H_0+A\cdot B$

$H'=eE_zz$

$er\cdot E$

$$\mathbf{0} \quad \boxed{\begin{matrix}\{\omega_y\omega_z\}\\ \{\omega_z\omega_x\}\\ \{\omega_x\omega_y\}\end{matrix}} \cdot \boxed{\begin{matrix}E_x\\ E_y\\ E_z\end{matrix}}$$

1) $H' = aE_z(\omega_x k_y - \omega_y k_x)$
Rashba

$(k \quad E)\cdot\omega$

2) $H'=b\rho\cdot\omega \; | \; \eta(\omega_x k_x - \omega_y k_y)$
Dresshauss

$\rho\cdot\omega$

E_z

$e_{xy}, P\iota(z-z_0)$

$H' \quad cE_z\{j_x j_y\}$

$\begin{pmatrix}\{j_y j_z\} \\ \{j_z j_x\} \\ \{j_x j_y\}\end{pmatrix} \cdot \begin{pmatrix}E_x \\ E_y \\ E_z\end{pmatrix}$

$E_z \qquad e_{xy}, P\iota(z-z_0)$

Rashba Dresshauss

H'

$H' \quad dJ\cdot\omega$

hole mixing
spin splitting

hole mixing effect

K 0

|3/2,3/2> |3/2, -1/2> |3/2, 1/2> |3/2,- 3/2>

$$\begin{pmatrix} H_{hh}(z) & & 0 & 0 \\ & H_{lh}(z) & 0 & 0 \\ 0 & 0 & H_{lh}(z) & 0 \\ 0 & 0 & 0 & H_{hh}(z) \end{pmatrix} \begin{bmatrix} \lambda_{hh}(z) \\ \lambda_{lh}(z) \\ \lambda_{lh}(z) \\ \lambda_{hh}(z) \end{bmatrix} | E \begin{bmatrix} \lambda_{hh}(z) \\ \lambda_{lh}(z) \\ \lambda_{lh}(z) \\ \lambda_{hh}(z) \end{bmatrix}$$

$$H_{hh}(z)\lambda_{hh}(z) \mid E\lambda_{hh}(z) \qquad for \qquad \left|3/2, \quad \partial 3/2\right\rangle$$

$$H_{lh}(z)\lambda_{lh}(z) \mid E\lambda_{lh}(z) \qquad for \qquad \left|3/2, \quad \partial 1/2\right\rangle$$

$$\Phi_{hh} \mid \lambda_{nhh}(z)\left|3/2, \quad \partial 3/2\right\rangle$$

$$\Phi_{lh} \mid \lambda_{mlh}(z)\left|3/2, \quad \partial 1/2\right\rangle$$

(

K 0

$$H \mid H_0 \, 2 \, F(z)'' \hat{J}_x \hat{J}_y €$$

e_{xy}, E_z , $P\iota(z\text{-}z_0)$

$$H(z) \mid \begin{pmatrix} H_{hh} & iF(z) & 0 & 0 \\ 4\, iF(z) & H_{lh} & 0 & 0 \\ 0 & 0 & H_{lh} & iF(z) \\ 0 & 0 & 4\, iF(z) & H_{hh} \end{pmatrix}$$

$$H_{hh}(z)\lambda_{hh}(z) \, 2 \, iF(z)\lambda_{lh}(z) \mid E\lambda_{hh}(z)$$

$$H_{lh}(z)\lambda_{lh}(z) \, 4 \, iF(z)\lambda_{hh}(z) \mid E\lambda_{lh}(z)$$

$$\boxed{\begin{aligned}&\Phi_{nh} \mid \lambda_{nh}(z)\left|3/2,\quad \partial\, 3/2\right\rangle 2\, i\,\zeta\lambda_{ml}(z)\left|3/2,\quad \mp 1/2\right\rangle\\&\Phi_{mh} \mid \lambda_{ml}(z)\left|3/2,\quad \mp 1/2\right\rangle 2\, i\,\zeta\lambda_{nh}(z)\left|3/2,\quad \partial\, 3/2\right\rangle\end{aligned}}$$

$$\zeta^2 \left|E_{nh} \; 4 \; E_{ml}\right| / 2$$

$$\zeta \mid \frac{\big| \lambda_{nh}(z) F(z) \lambda_{ml}(z) dz}{\mid E_{nh} \; 4 \; E_{ml} \mid}$$

1

1

2

3

4

XY

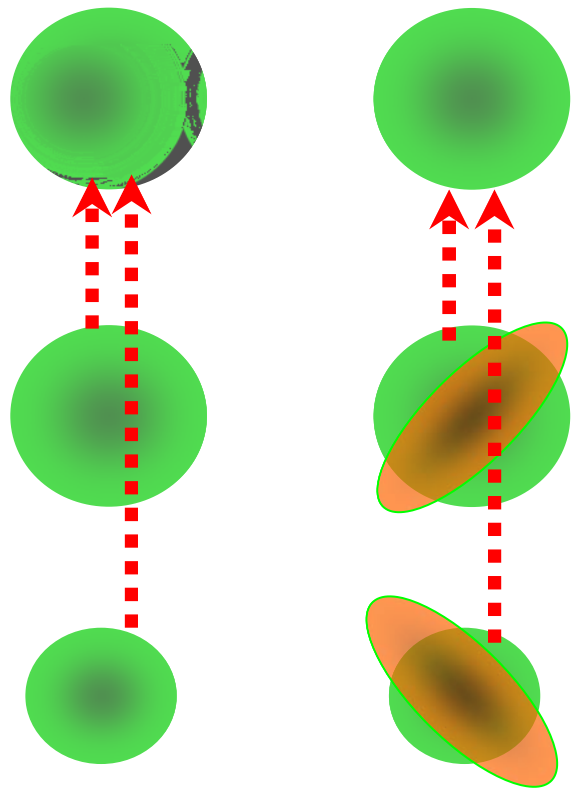
$|s>$

$\left|3/2,\ \ 3/2\right\rangle$

$\frac{1}{\sqrt{2}}/X\ 2\,iY\,\mathbb{0}\Rightarrow$

$\left|3/2,\ \ 4\,1/2\right\rangle$

$\frac{1}{\sqrt{6}}\Psi/X\ 4\,iY\,\mathbb{0}\Rightarrow 22Z\Leftrightarrow\beta$

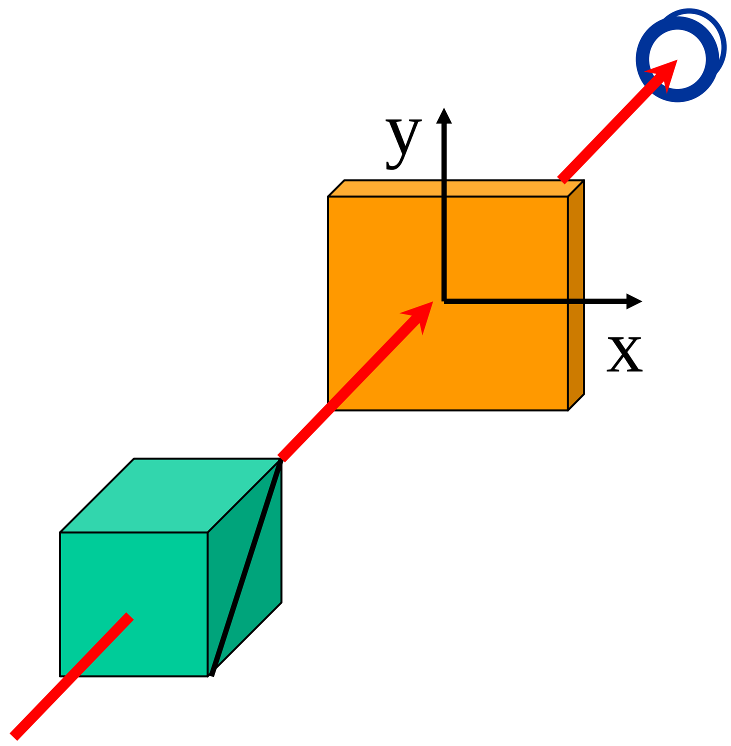


$f(r)\,2\,\zeta XY$

$g(r)\,4\,\zeta XY$

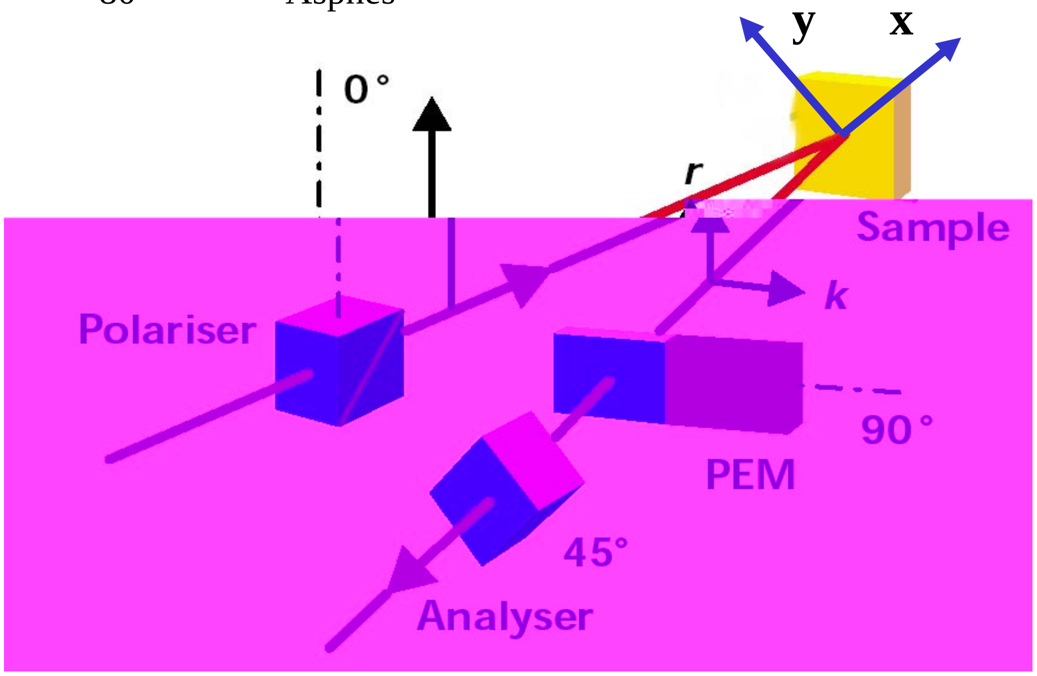
$$P \mid \frac{I_x \; 4 \; I_y}{I_x \; 2 \; I_y}$$

5



reflectance difference spectroscopy (RDS)

80 Aspnes



$÷r/r=2(r_x-r_y)/(r_x+r_y)$

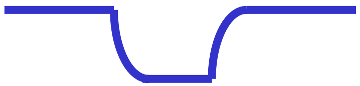
10^{-5}

RDS

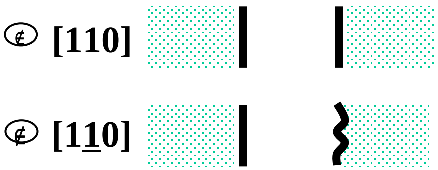
RDS SCI

RDS

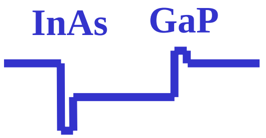
InGaAs/GaAs



GaAs/AlGaAs



InGaAs/InP



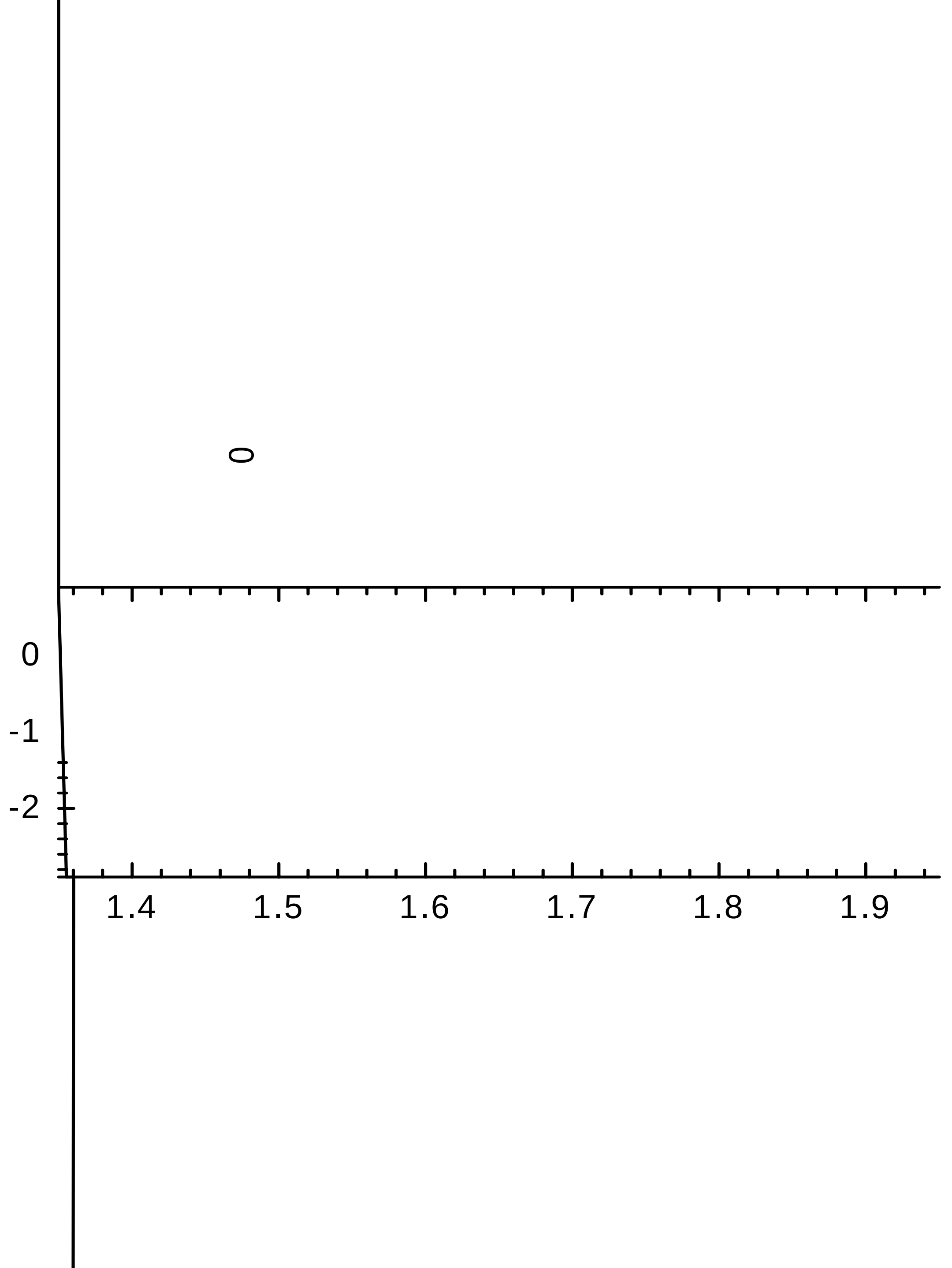
GaAs/AlGaAs ——

InGaAs/GaAs——In

InGaAs/InP——

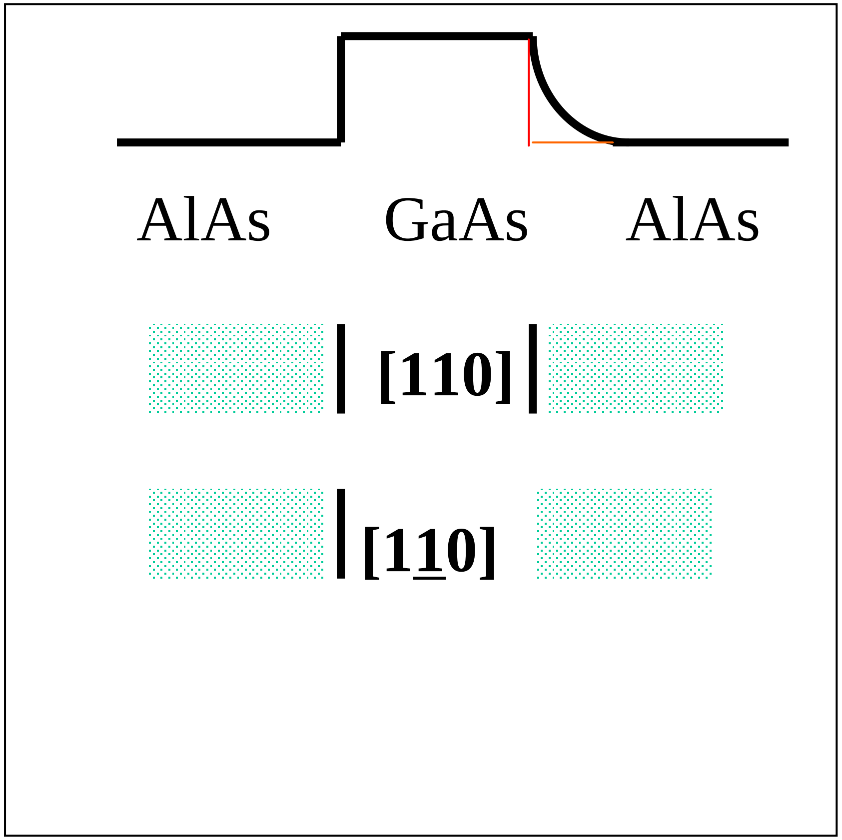
GaNAs/GaAs , GeSi/Si

InAs/GaAs **InAs**


0
0
-1
-2
1.4
1.5
1.6
1.7
1.8
1.9

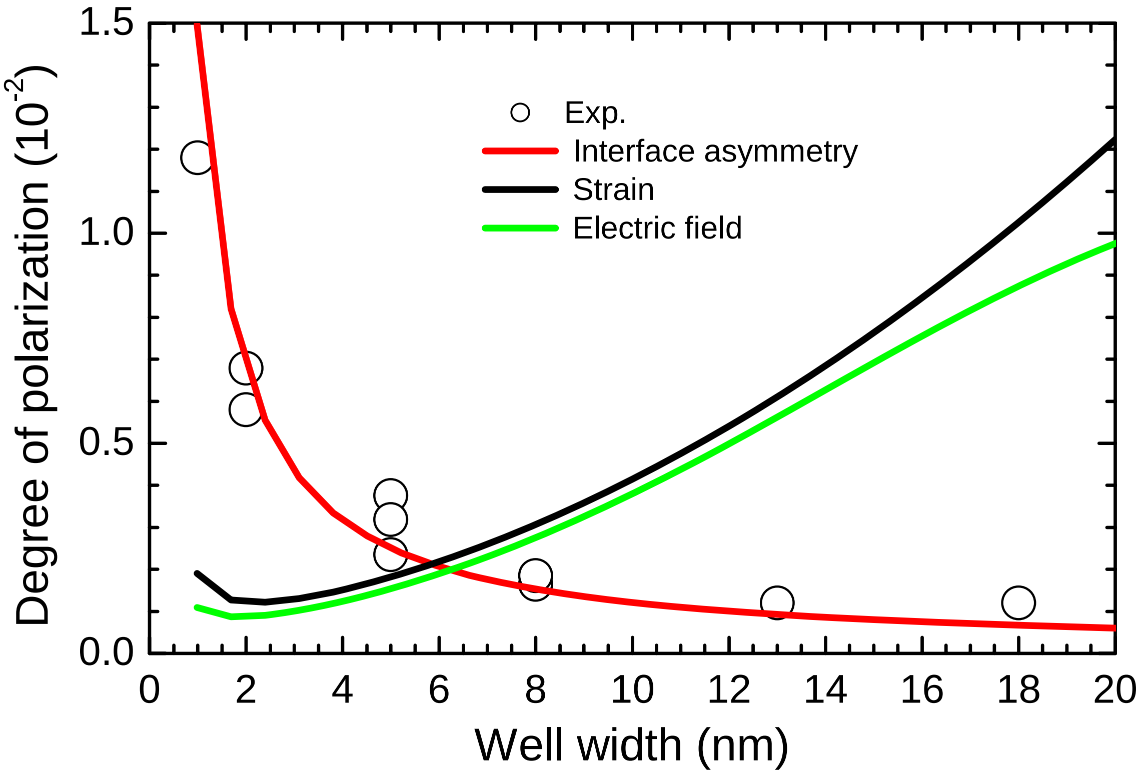
GaAs/AlGaAs

Ga



$$P_1 \iota \ \ (z\ 2\ w/2)\ 4\ \frac{P_2}{l} \exp(\ 4\ \frac{z\ 4\ w/2}{l}) \mathrm{N}(z\ 4\ w/2)$$

GaAs/AlGaAs 1H1E



1.5

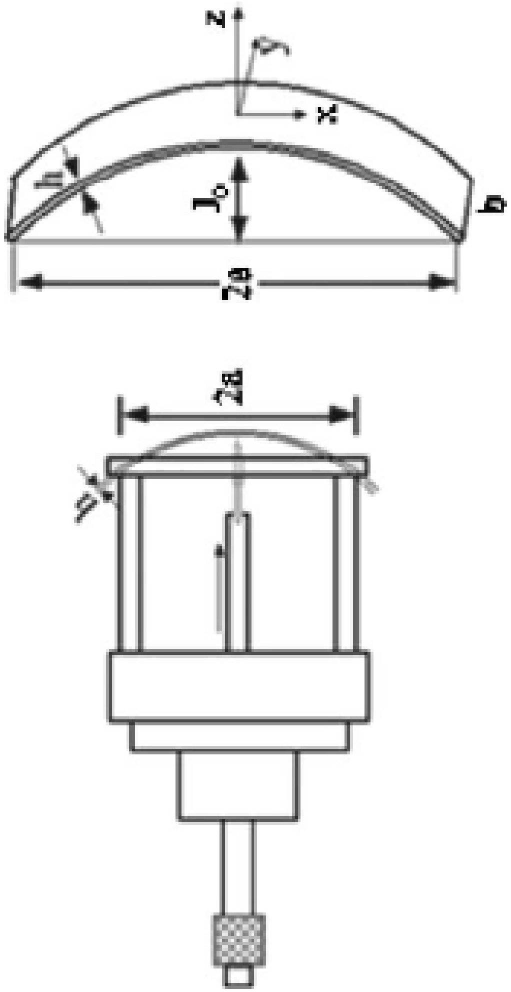
( ):

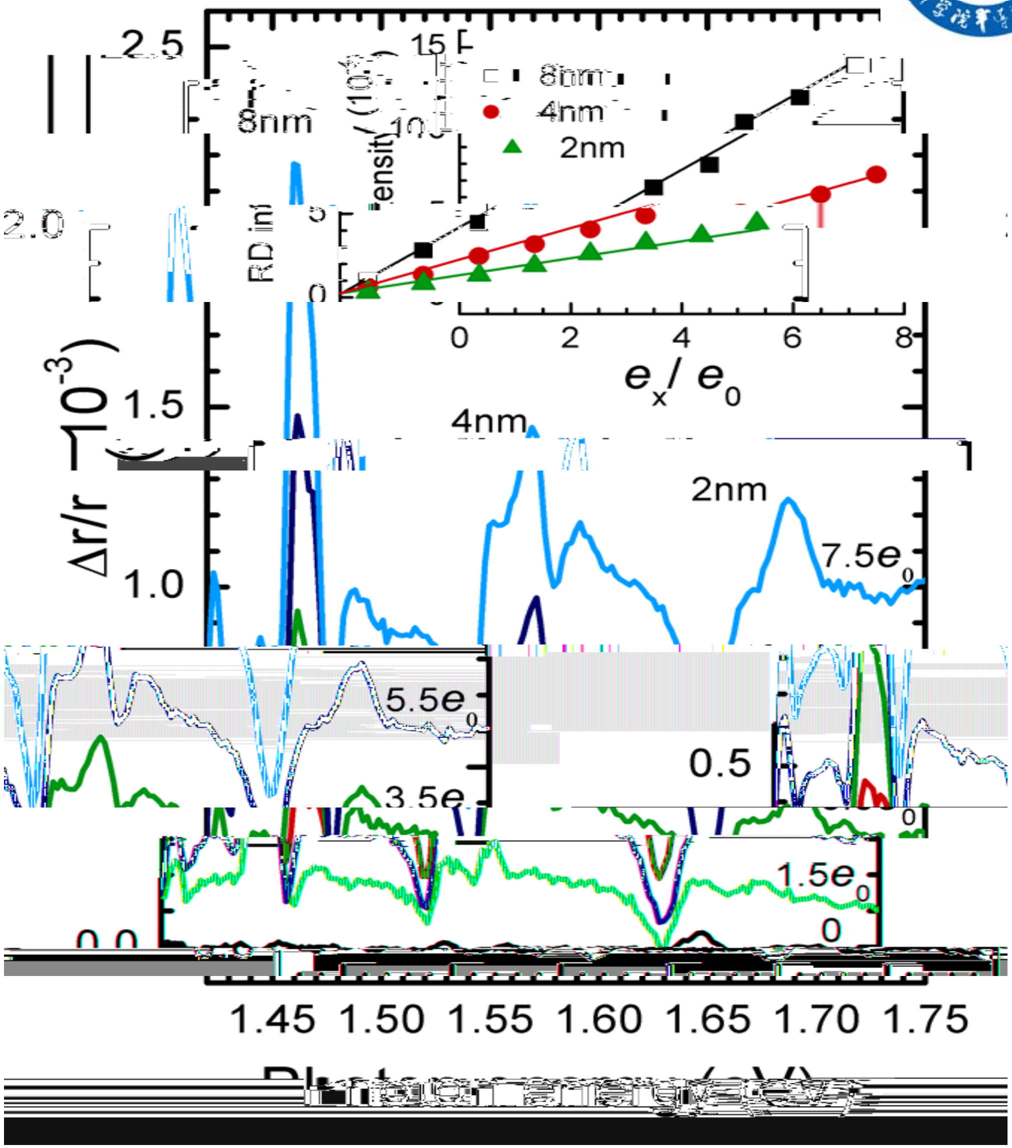
$$\frac{\langle 1H \,|\, F(z) \,|\, 1L \rangle}{\div E}$$

$$\div E \nabla 1/w^2$$

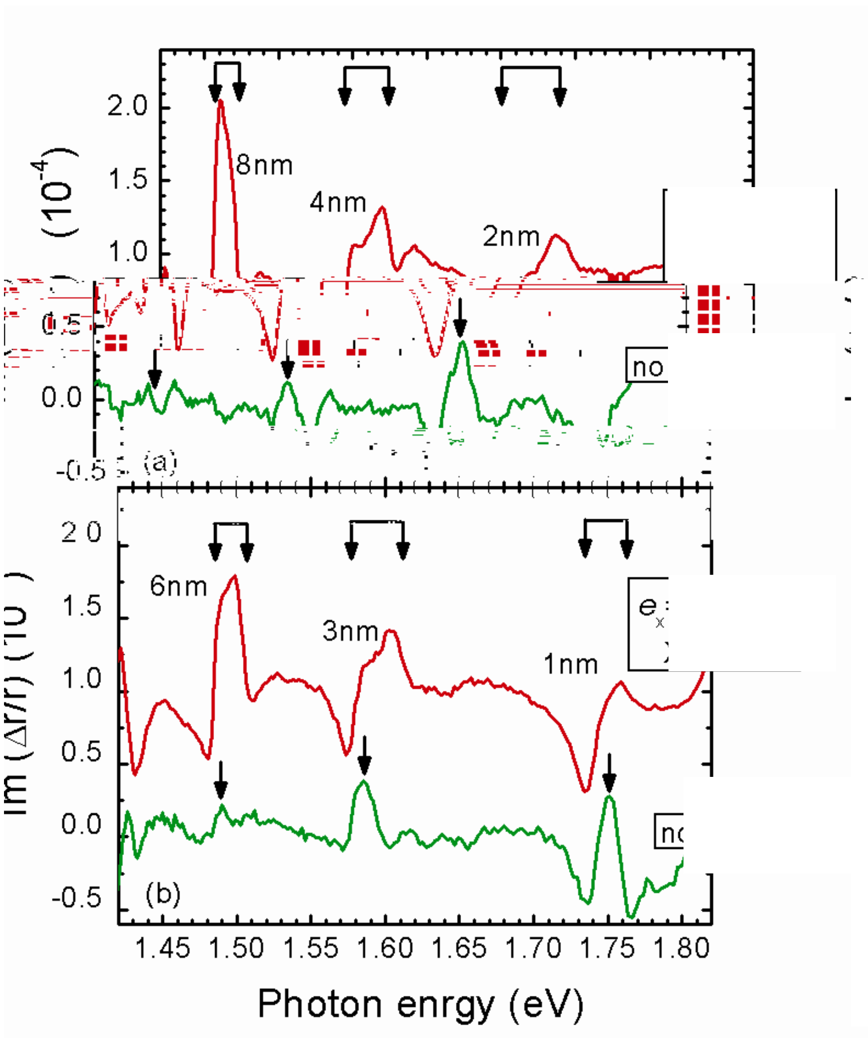
$$\langle 1H \,|\, F(z) \,|\, 1L \rangle$$

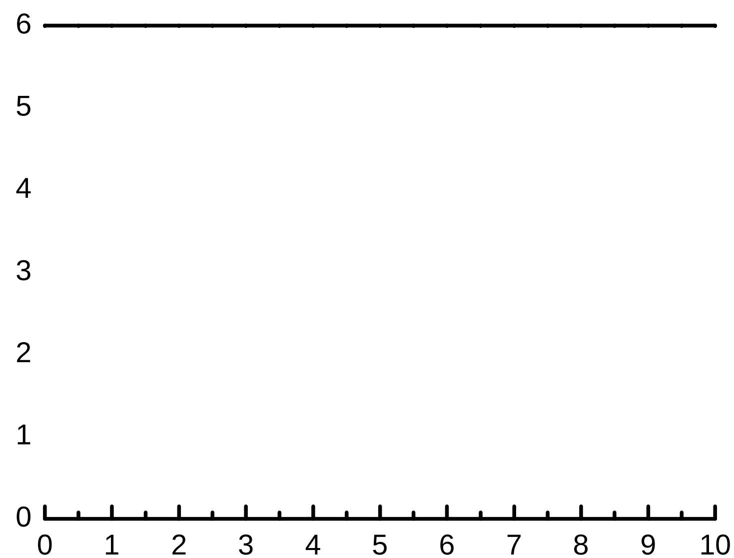
e_{xy}, E_z





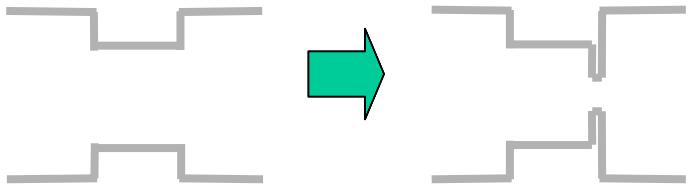
GaAs/AlGaAs RDS





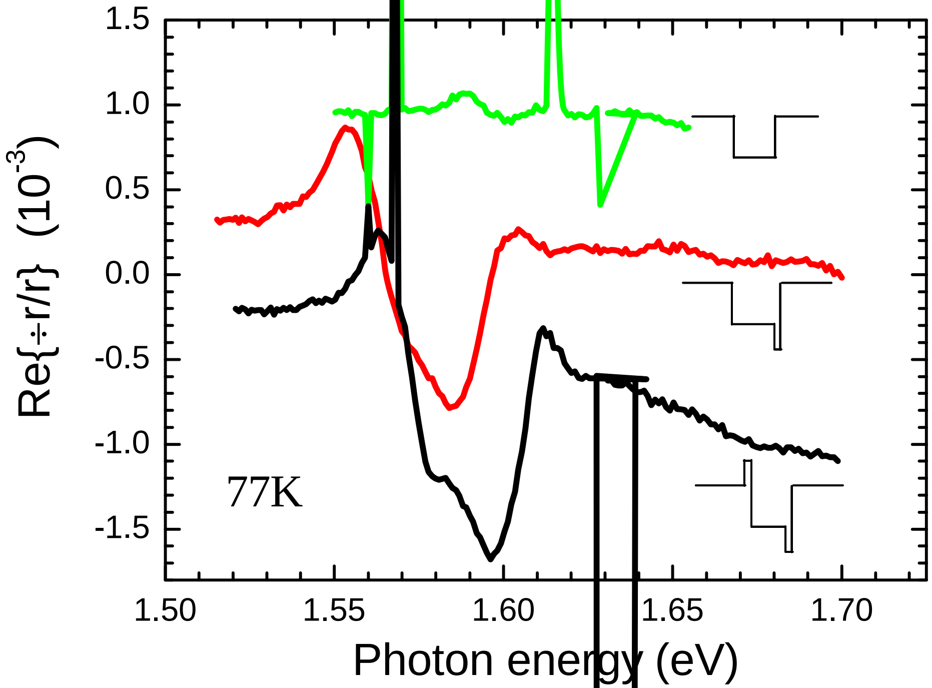
GaAs/AlGaAs

RDS



1ML InAs

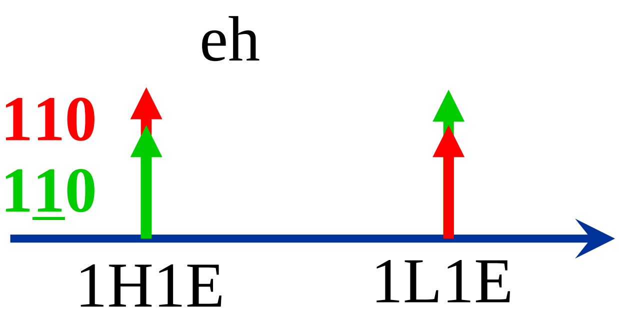
GaAs/AlGaAs



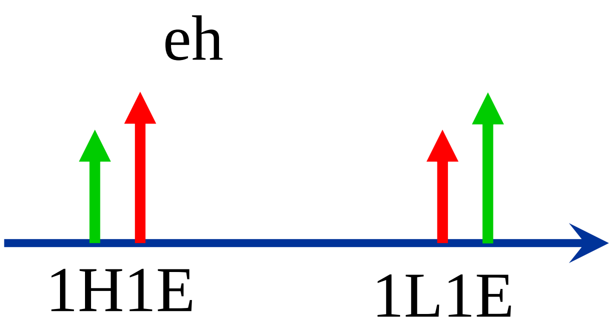
C_{2V} ⇓

$$H' \mid a\vec{J}\vec{\omega}\, 2\, F(z)'' J_x J_y €$$

1H 1L



÷M(hh) = -÷M(lh)



÷M(hh) = -÷M(lh)
÷E(hh) = -÷E(lh)

$$\div E \nabla \frac{F_{hl} E_{eh}}{\div E_{hl}}$$

10 100σeV

☑ C_{2V}

☑

☑

ODMR II GaAs/AlAs

I

RDS

$\div \kappa_s$

κ_s :

$$\Delta \varepsilon_s = -\Delta E_s \frac{d\varepsilon_s}{dE} + 2P_s \varepsilon_s$$

$$\boxed{2\,\mathrm{Re}\left[\frac{\div r}{r}\right] \mid 4 \div E_s \frac{d \ln R}{dE}\; 2\, P_s \frac{\div R}{R}}$$

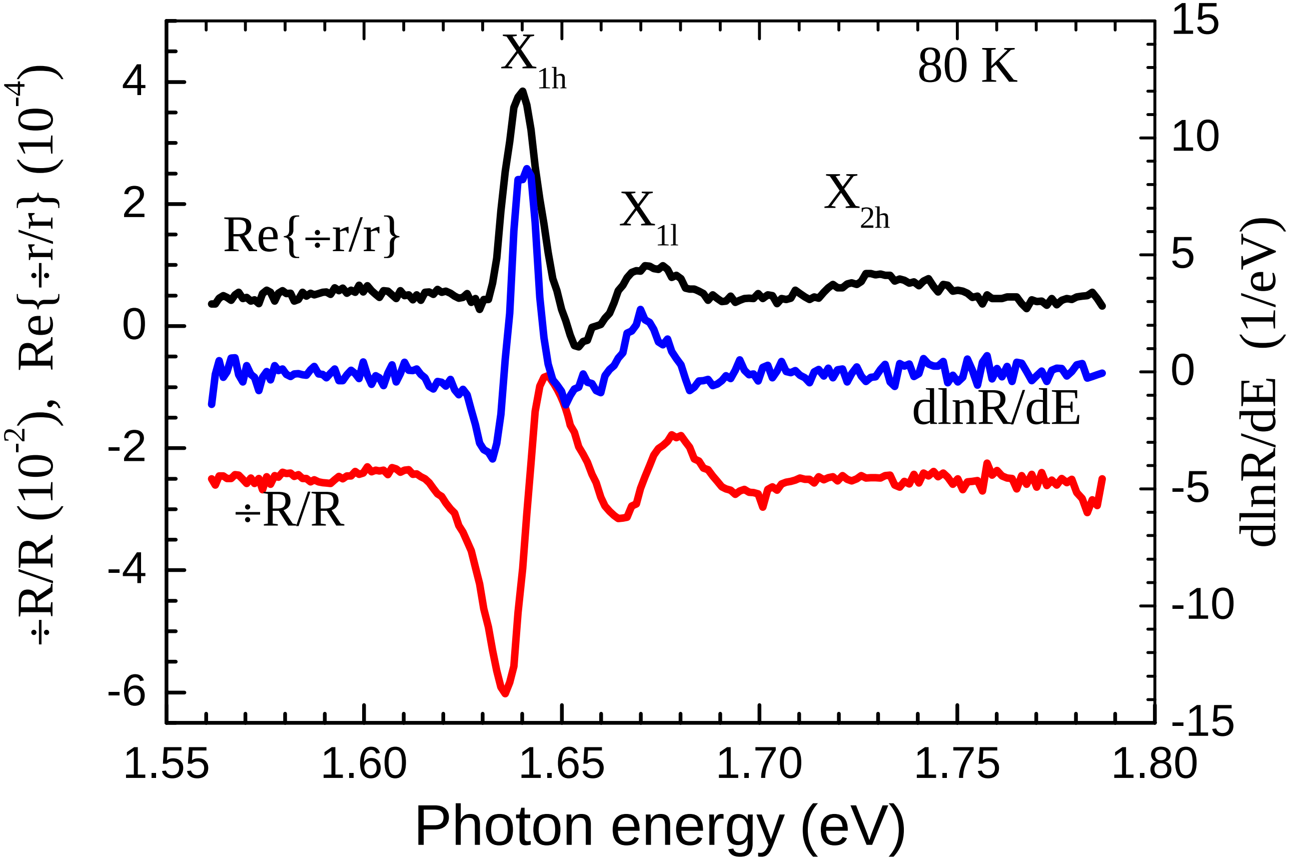
RDS **$\div E_s$**

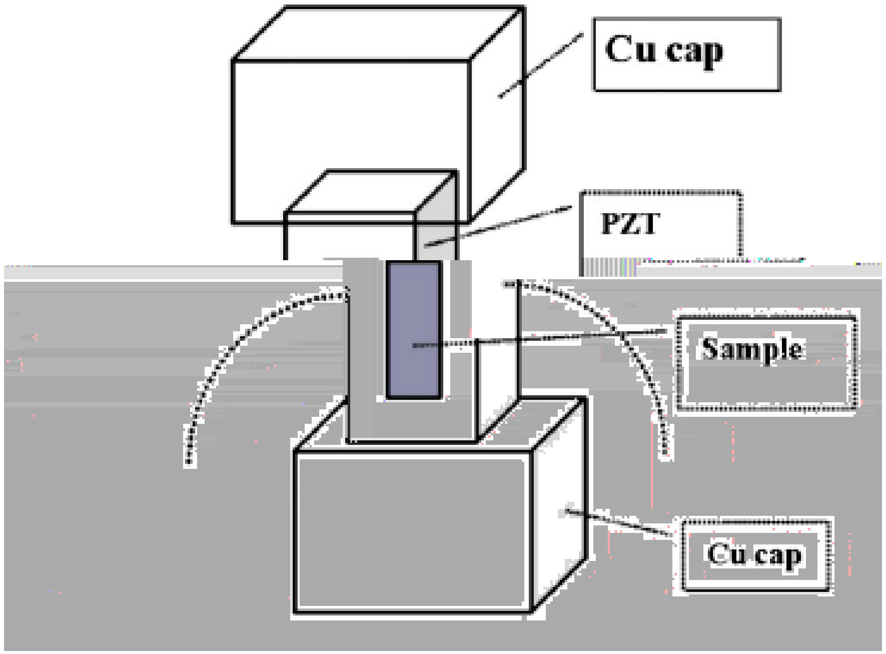
P_s

I

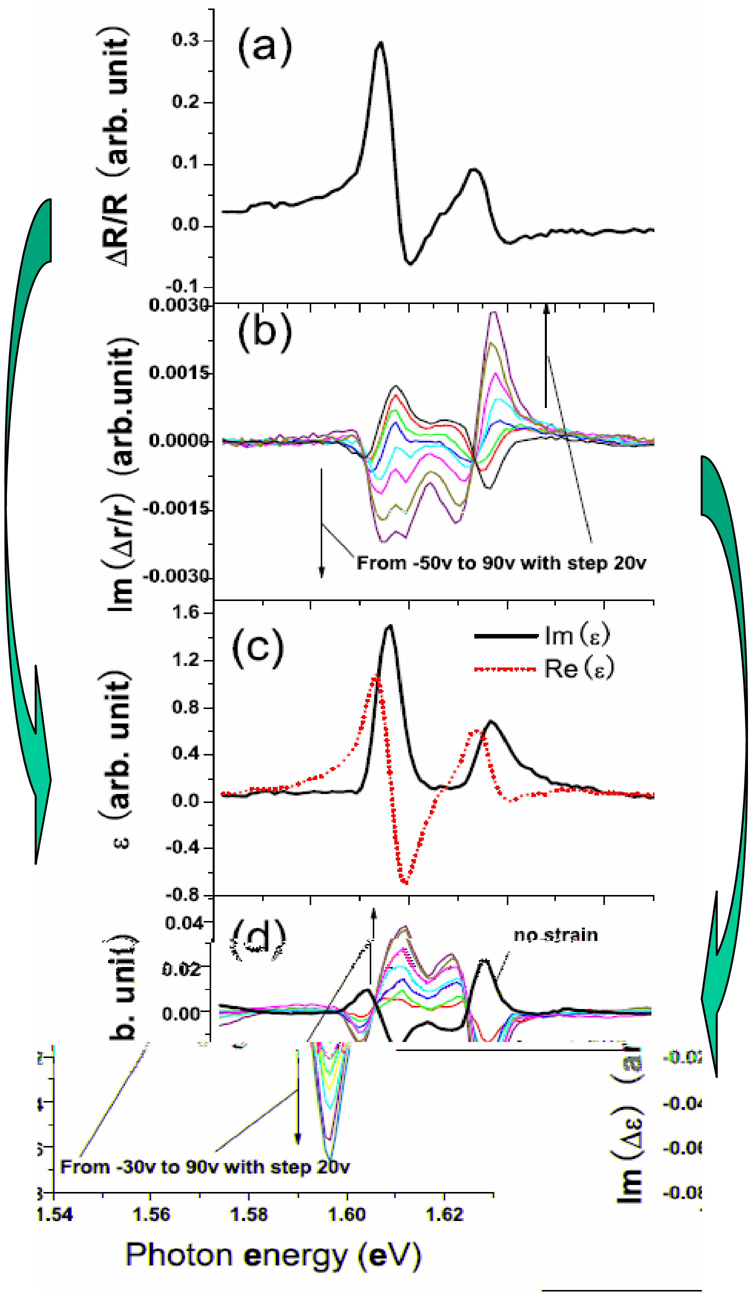
5nm-GaAs/$Al_{0.36}Ga_{0.64}As$

÷E=64σeV; P=0.008




Cu cap
PZT
Sample
Cu cap

80K RDS

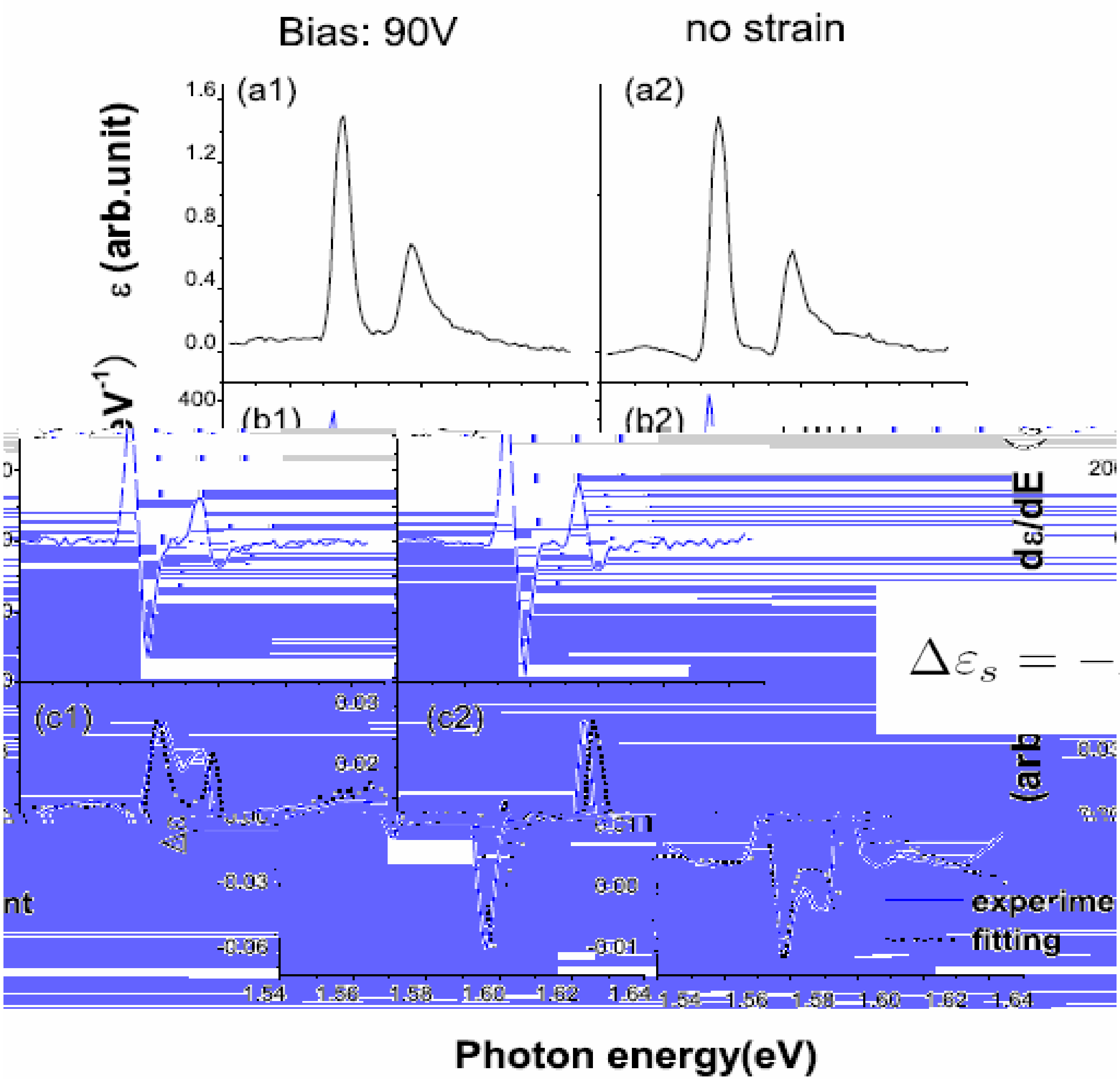


RDS

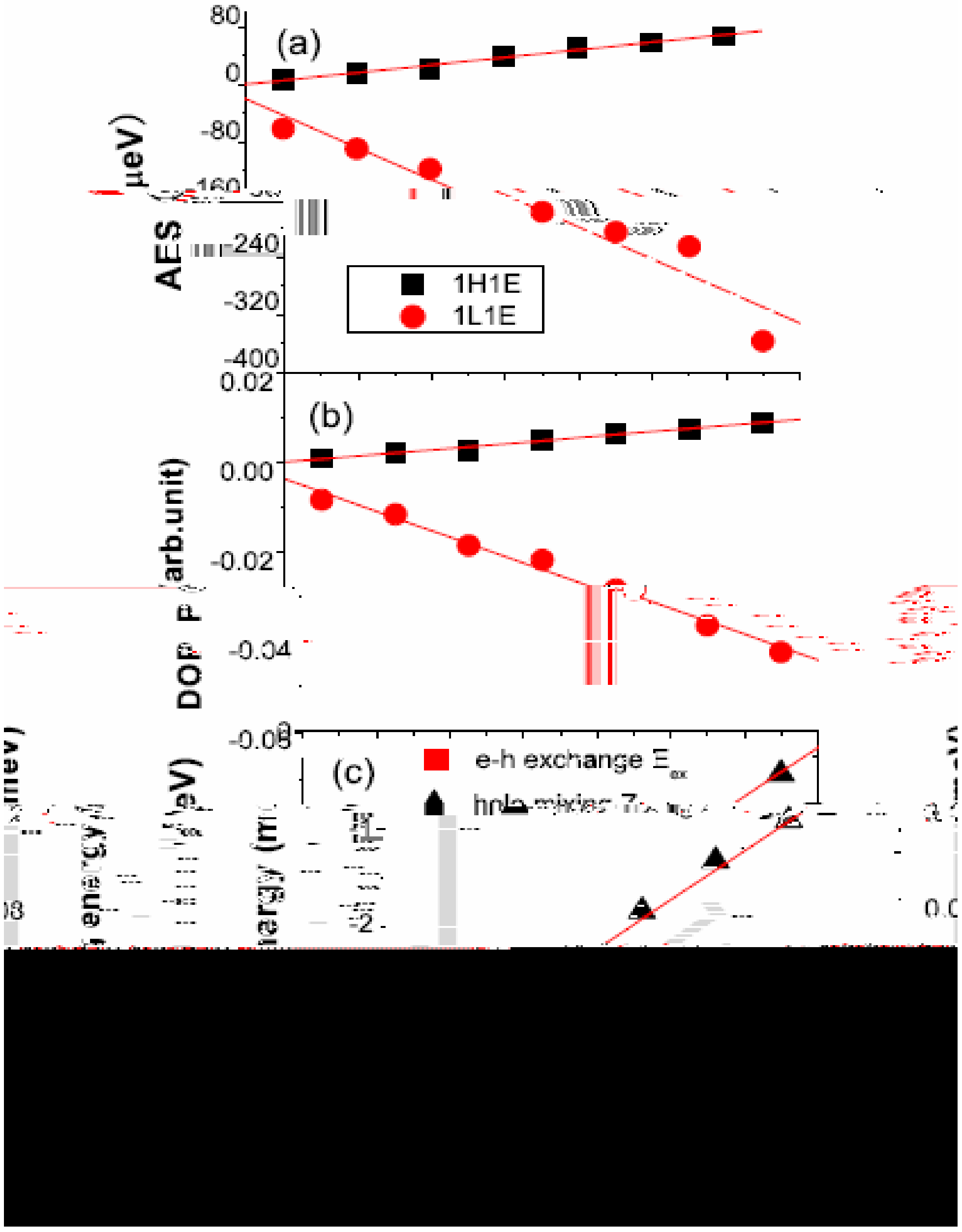
QW

QW

$$\Delta\varepsilon_s = -\Delta E_s \frac{d\varepsilon_s}{dE} + 2P_s\varepsilon_s$$



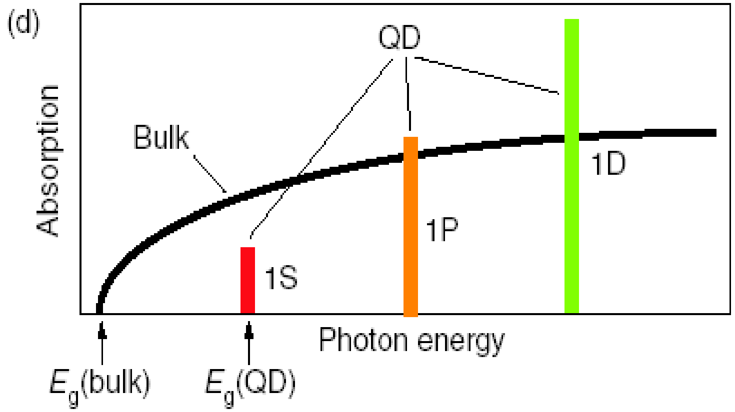
$$\Delta\varepsilon_s = -\Delta E_s \frac{d\varepsilon_s}{dE} + 2P_s\varepsilon_s$$


(a)
80
0
-80
-160
-240
-320
-400
μeV)
AES
1H1E
1L1E
0.02
(b)
0.00
-0.02
-0.04
arb.unit)
DOP
(c)
e-h exchange E
-0.08

InAs/GaAs

:

:



:

QD :

QD :

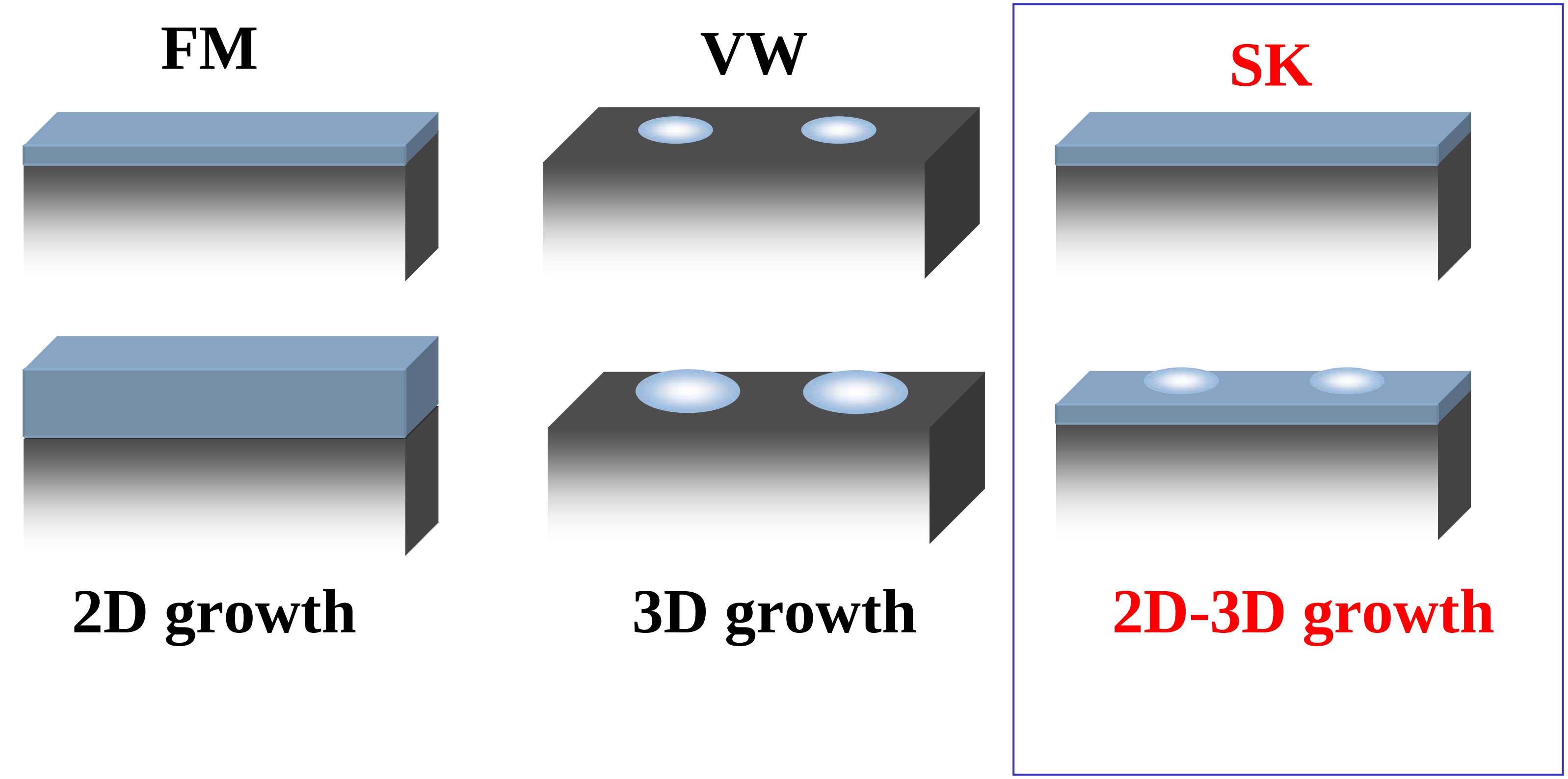
QD :

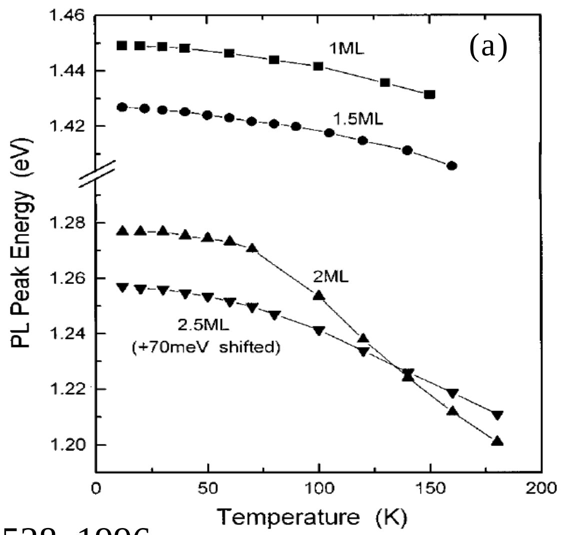
QD :

SK QDs

, , (WL)

3D





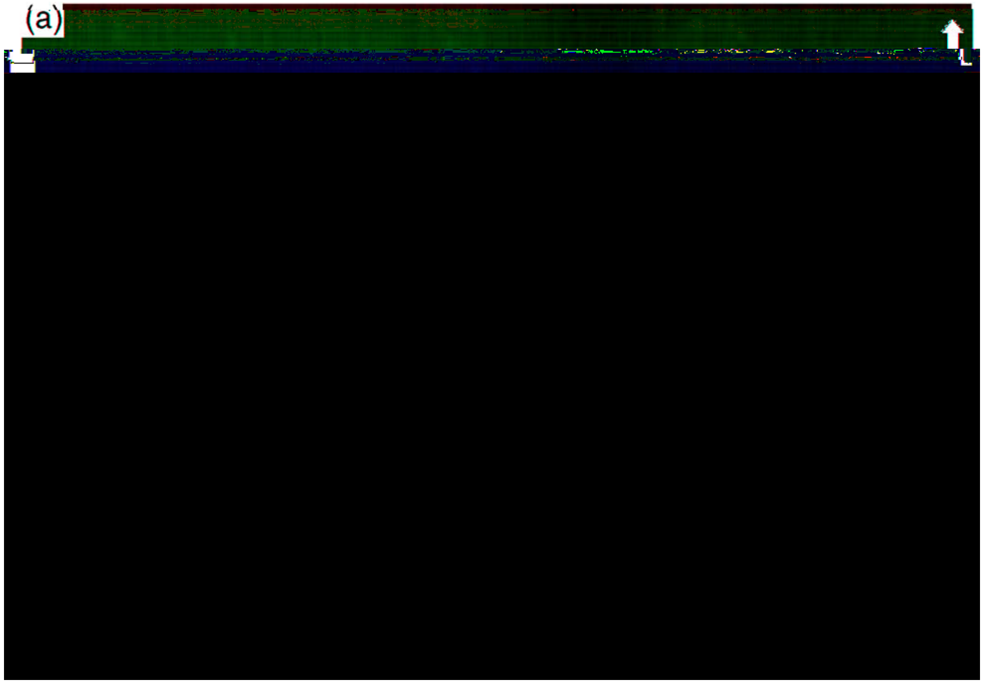
Phys. Rev. B 54, 11528, 1996

: WL QD

WL?

- XSTM

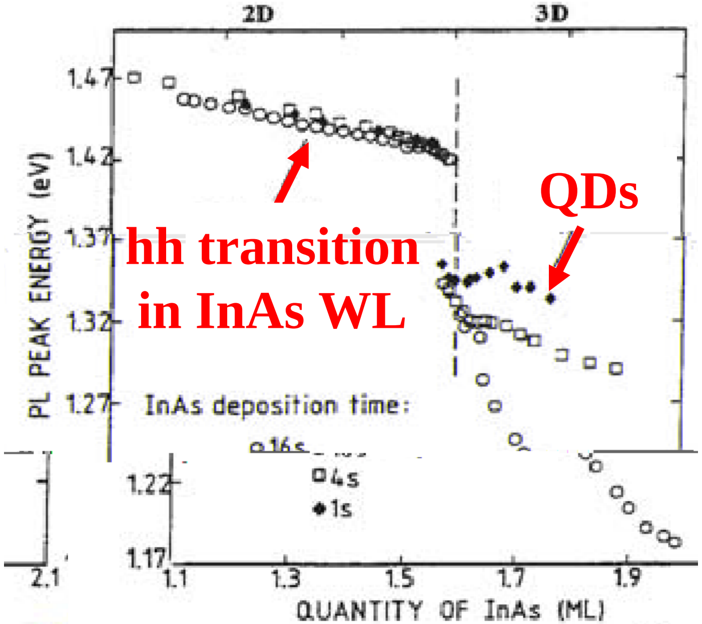
InAs WLs can be directly characterized by cross-sectional scanning tunneling microscopy.



APL. **87**, 111903 2005

Photoluminescence

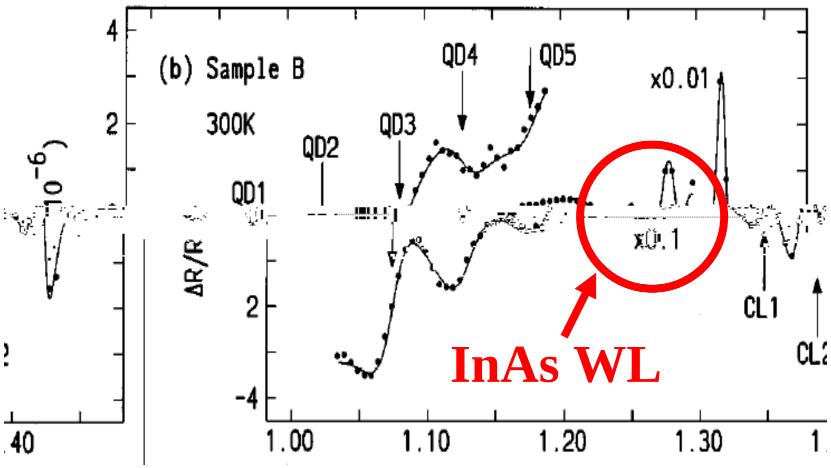
Usually hh is observable before QD formation



J Crystal Growth 150, 351(1995)

Photoreflectance

Both hh and lh are observed, but interfered with E_g signal



Appl. Phys. Lett. 73, 3268(1998)

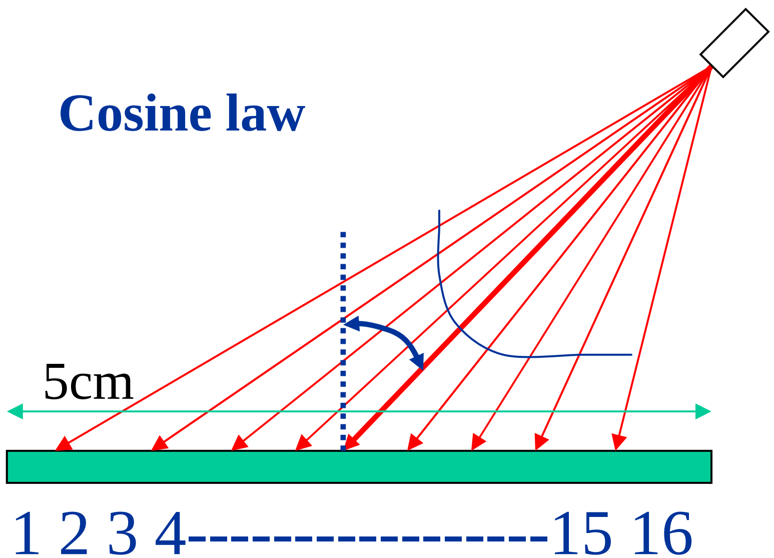
WL

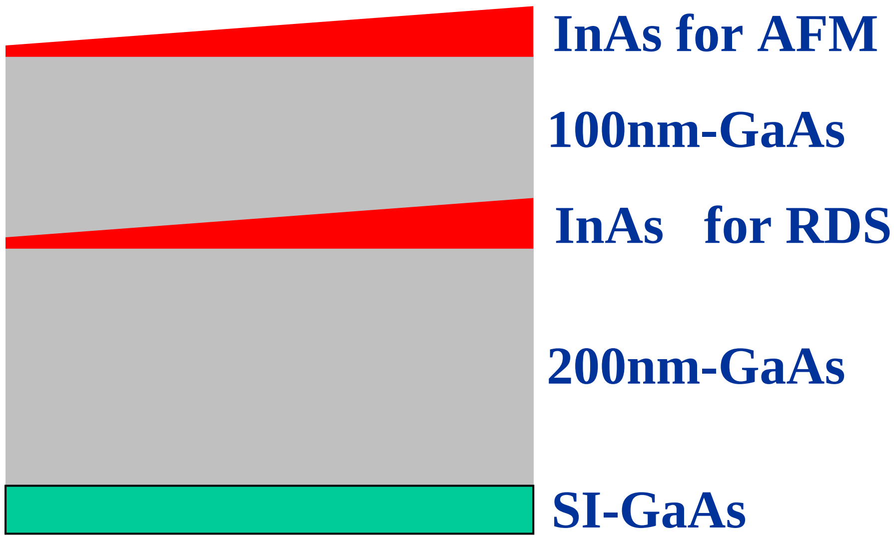
RDS InAs/GaAs QD

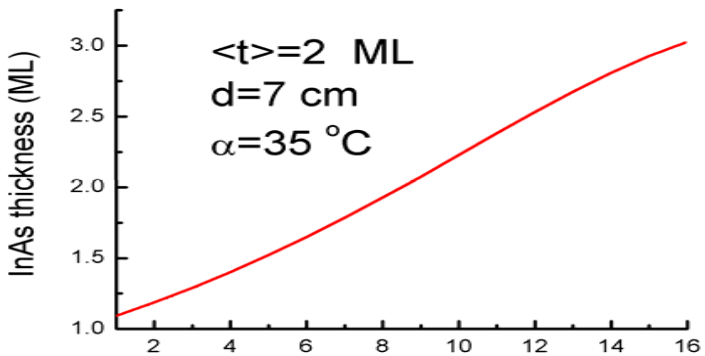
InAs QD —— InAs

- **In**
  RDS
- **GaAs**
  InAs
- **RDS**
  In ——In
  ——

•







<t>, ,

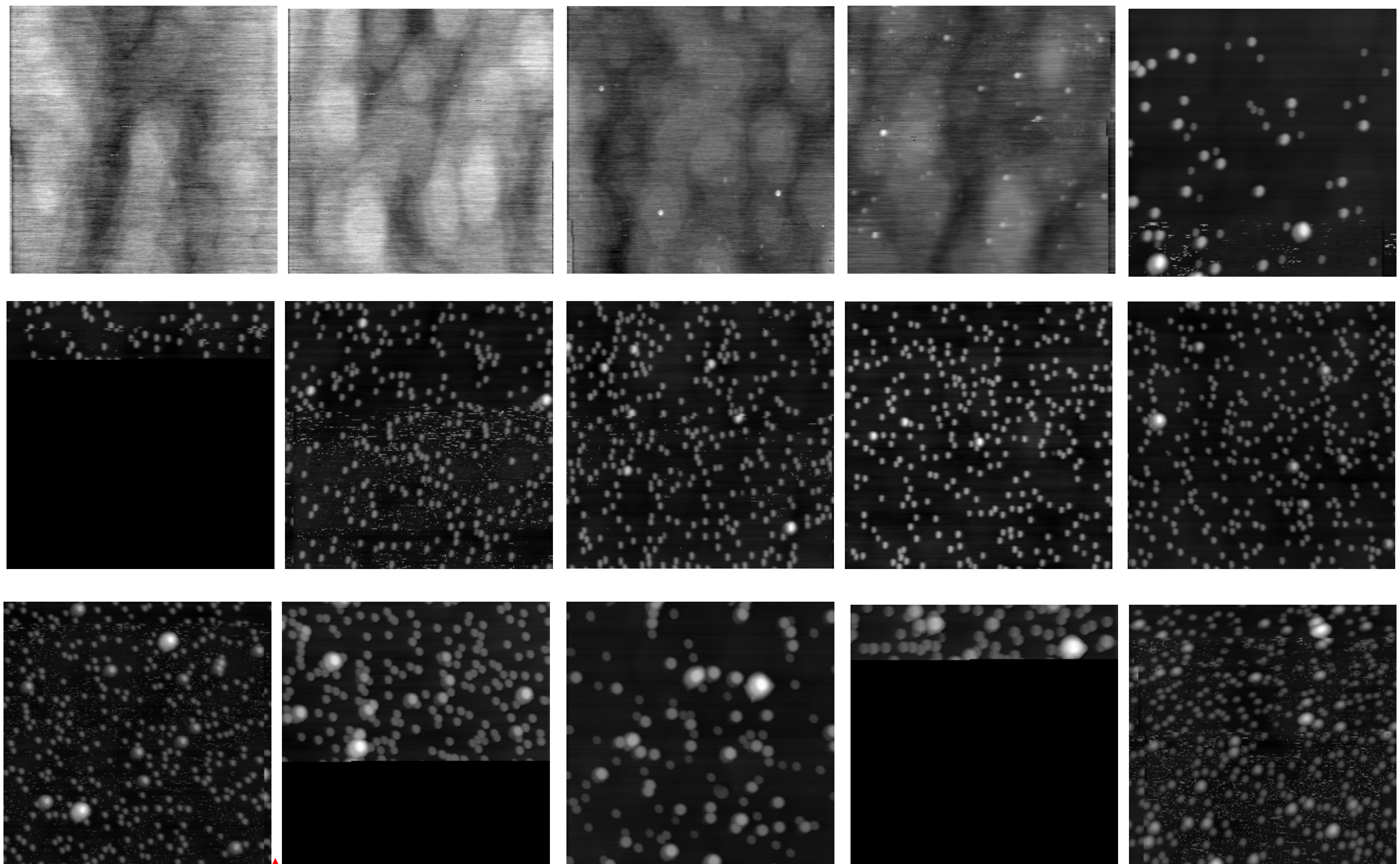
2.0ML **530ºC** **0.008ML/s**

QDs **WL**

2 **In**

AFM images

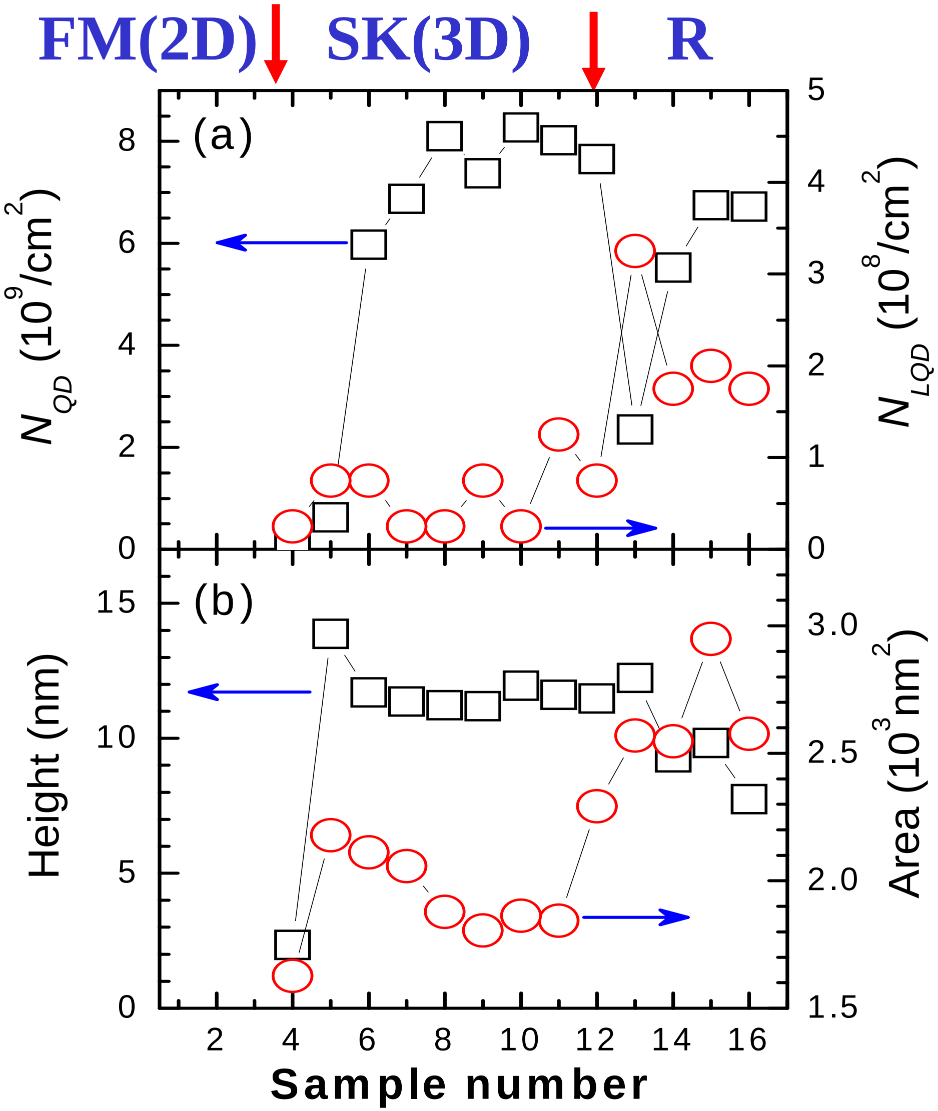
2 2 σm FM growth SK growth

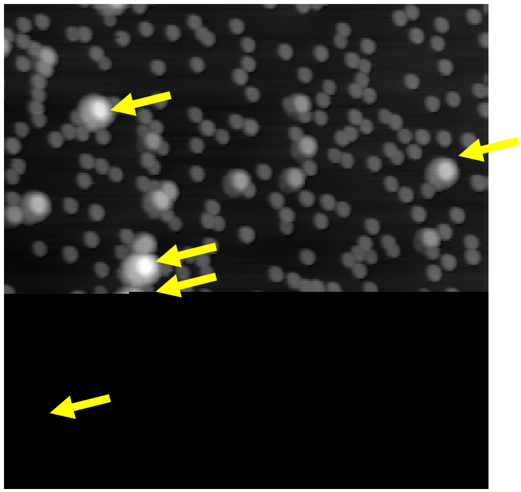


Ripening

InAs: 530^{o}C, 0.008ML/s

AFM results

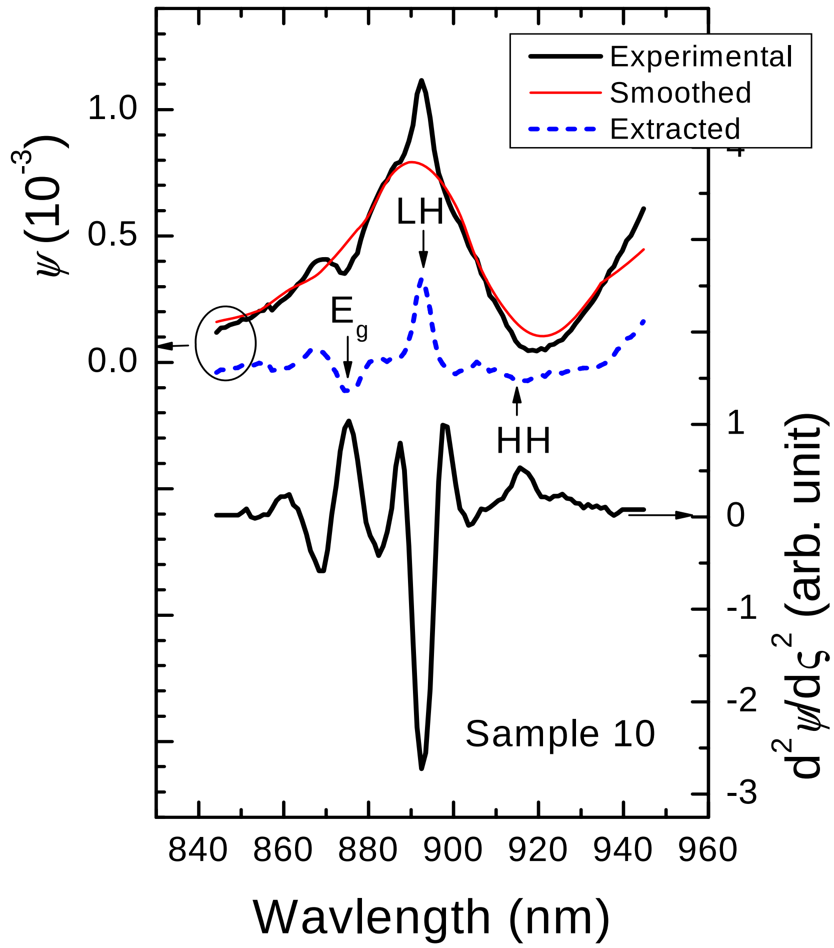




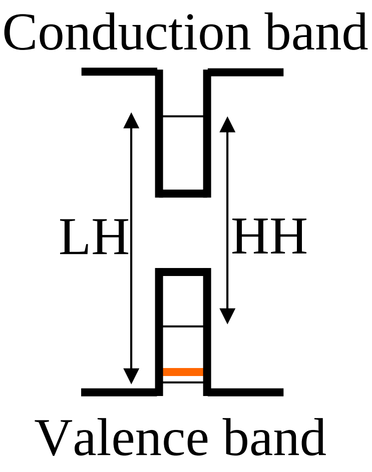
9-16: Huge dots

2 times larger in sizes

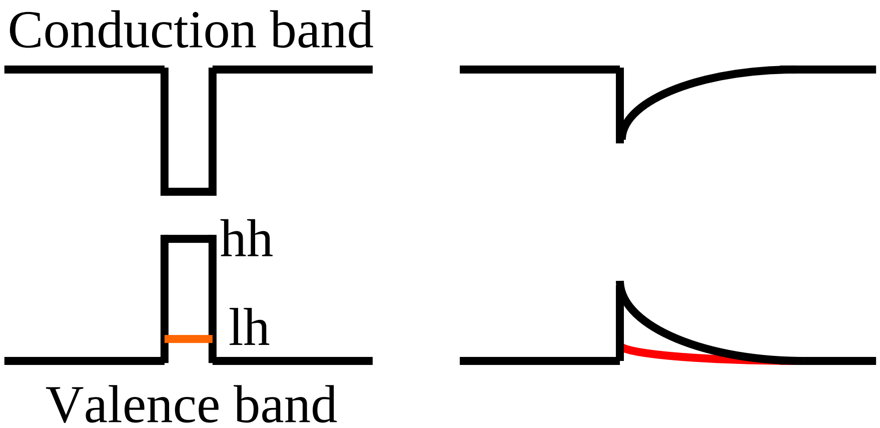
RDS 10th



WL as a thin QW



1) In



No segregation   Indium segregation

Indium composition distribution

$$X_{In} = \begin{cases} 0 & z < 0 \\ \dfrac{t_{WL}}{l}\exp(-z/l) & z > 0 \end{cases}$$

t_{WL}: **InAs amount in WL**

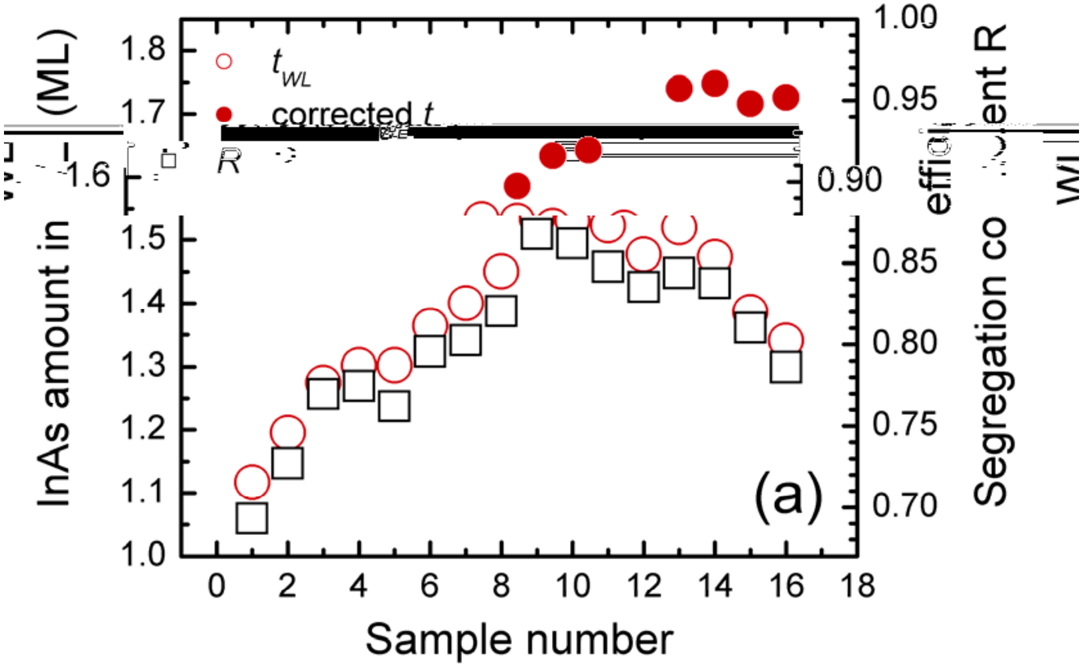
l : **segregation length**

2) : binding energies for hh and lh

3)

E_{hh}, E_{lh} ♥ t_{WL}, l

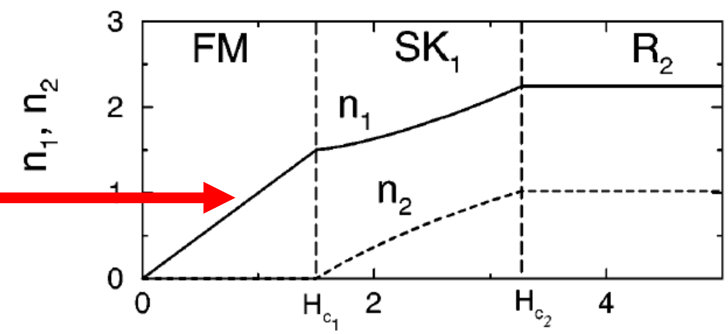
InAs In



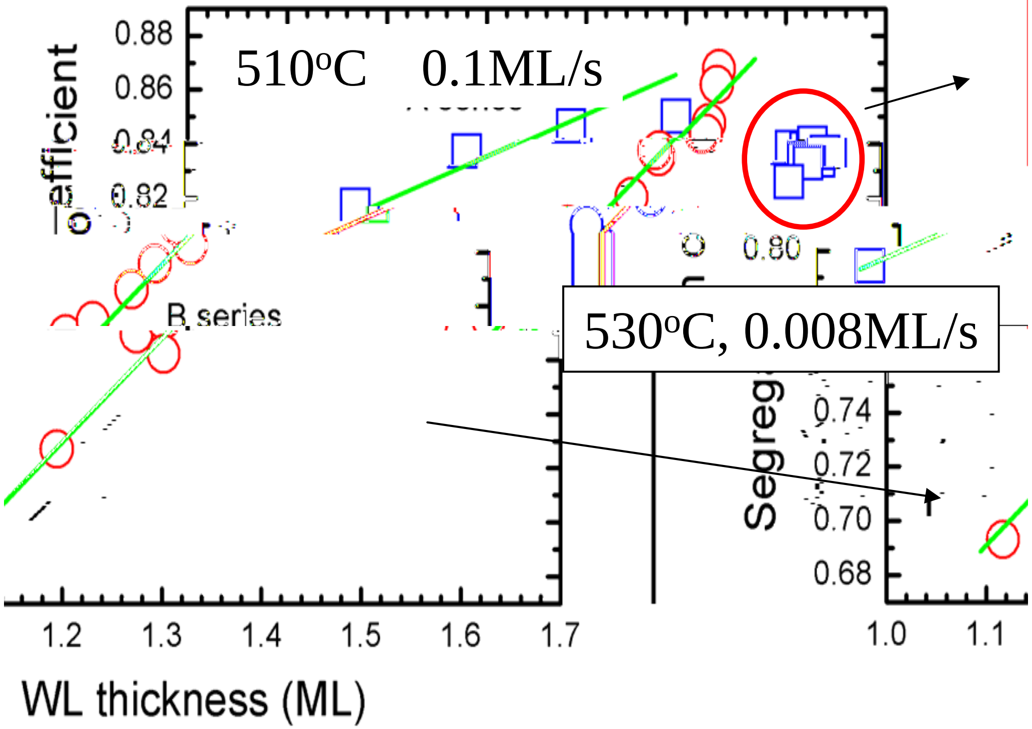
Phys. Rev. Lett. 79, 3708 (1997)

$\varepsilon_1 < \varepsilon < \varepsilon_2$

InAs WL



In InAs



QD

In

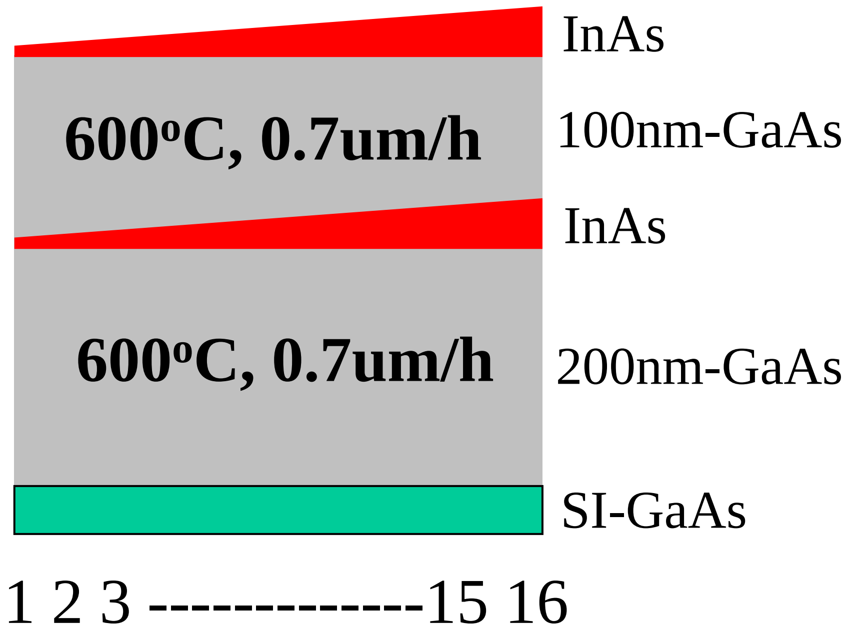
In

Ga

In

Segregation coefficient varies linearly with the InAs amount in WL before SK growth: **strain as driven force!**

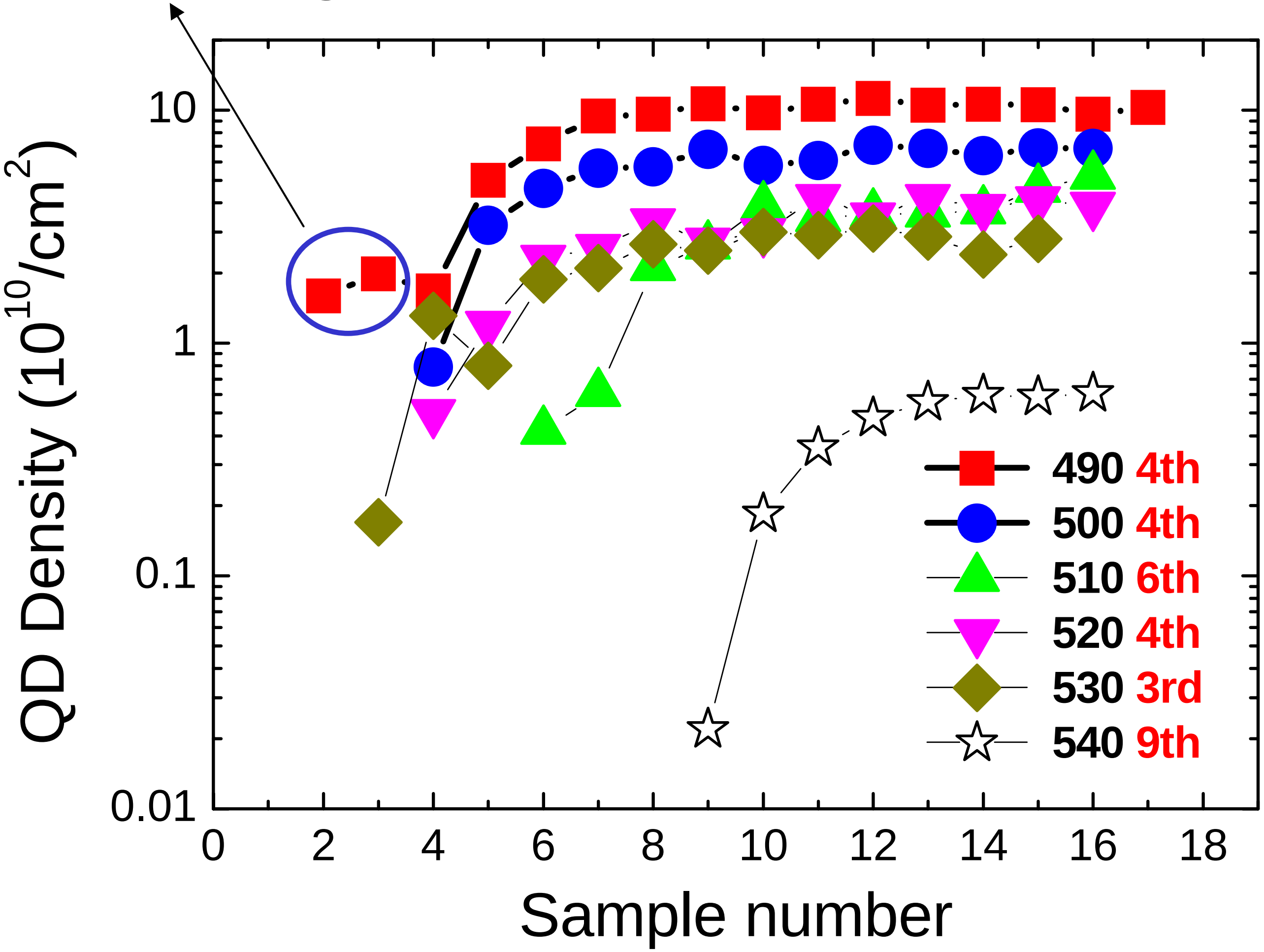
2D 3D



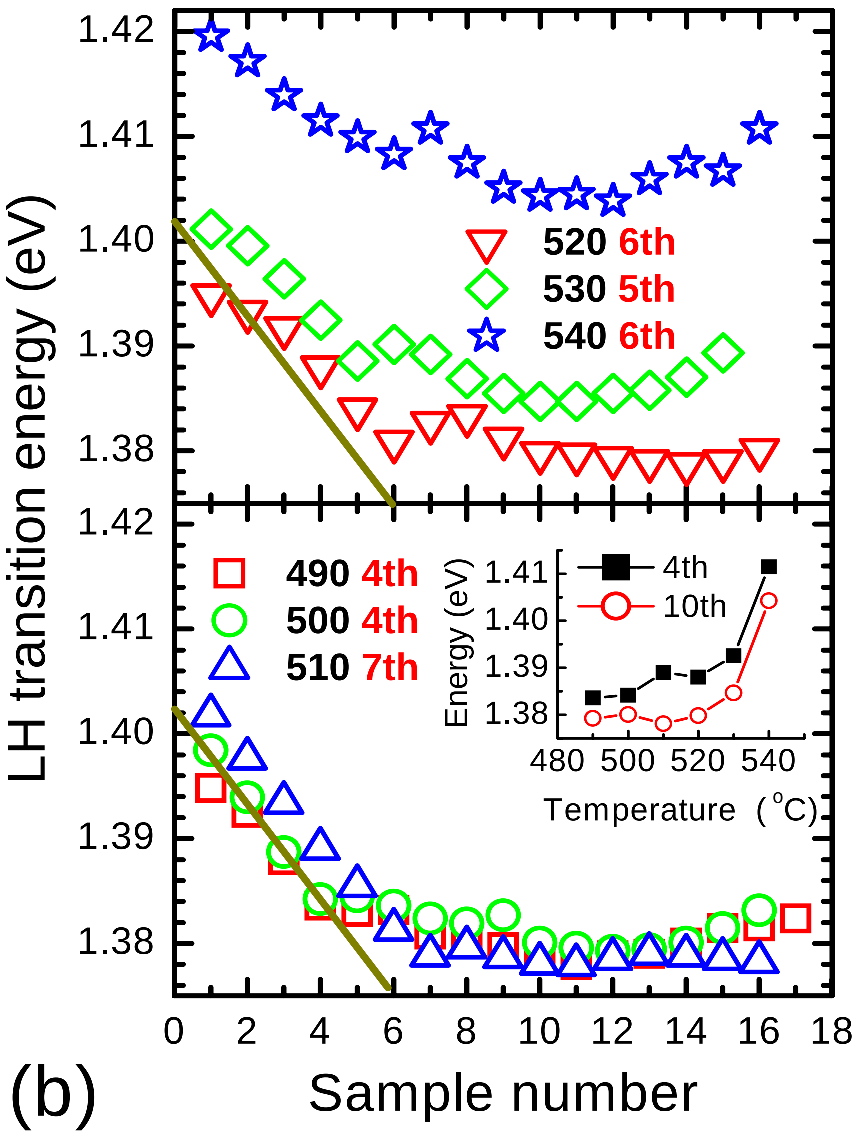
<t>,	Growth Temp,	Vg
2.0ML	490ºC	0.1ML/s
2.0ML	500ºC	0.1ML/s
1.9ML	510ºC	0.1ML/s
2.0ML	520ºC	0.1ML/s
2.0ML	530ºC	0.1ML/s
2.0ML	540ºC	0.1ML/s

QD AFM

2D islands, height<1nm



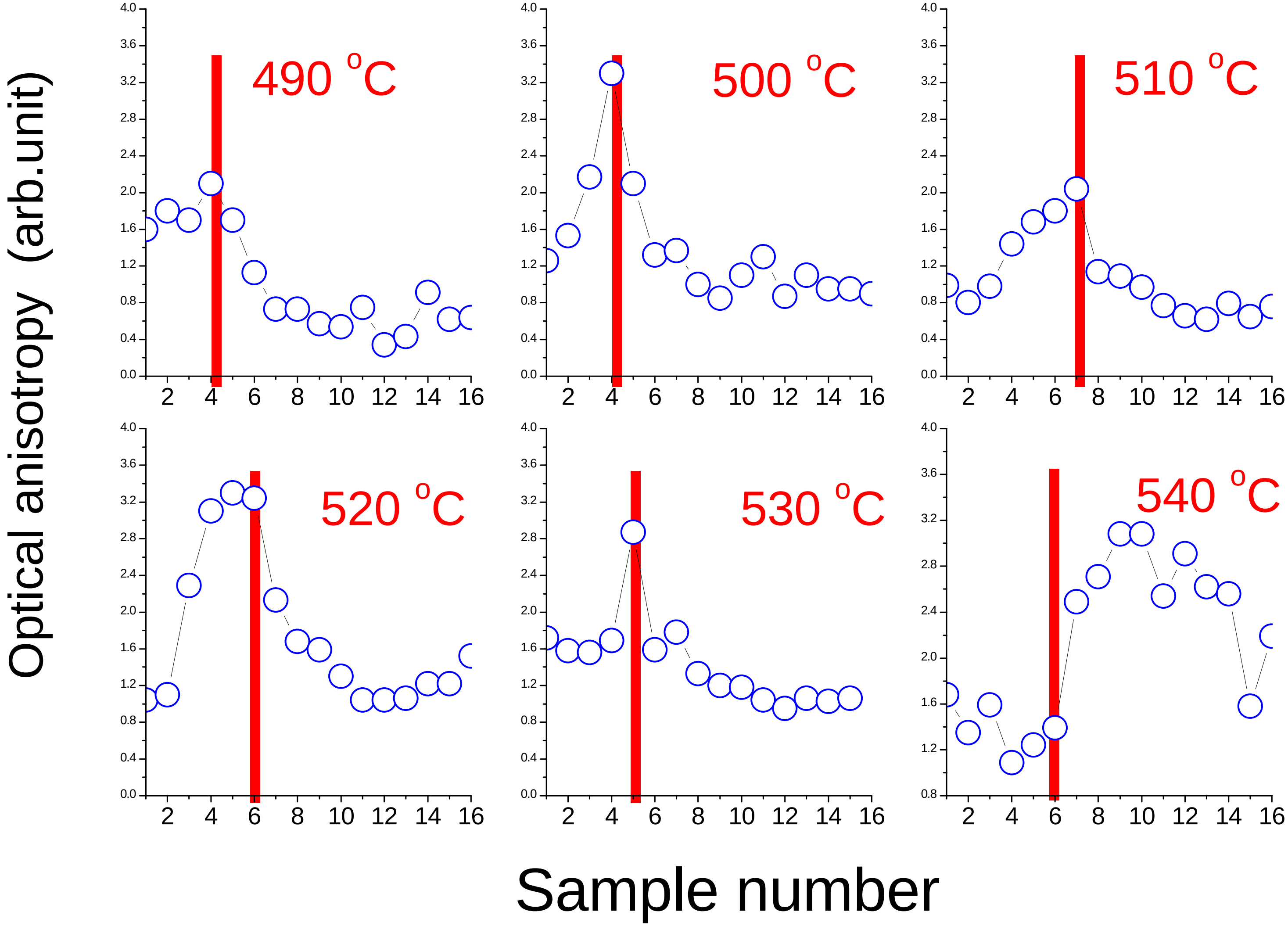
2D-3D : 3D-InAs



InAs

InAs

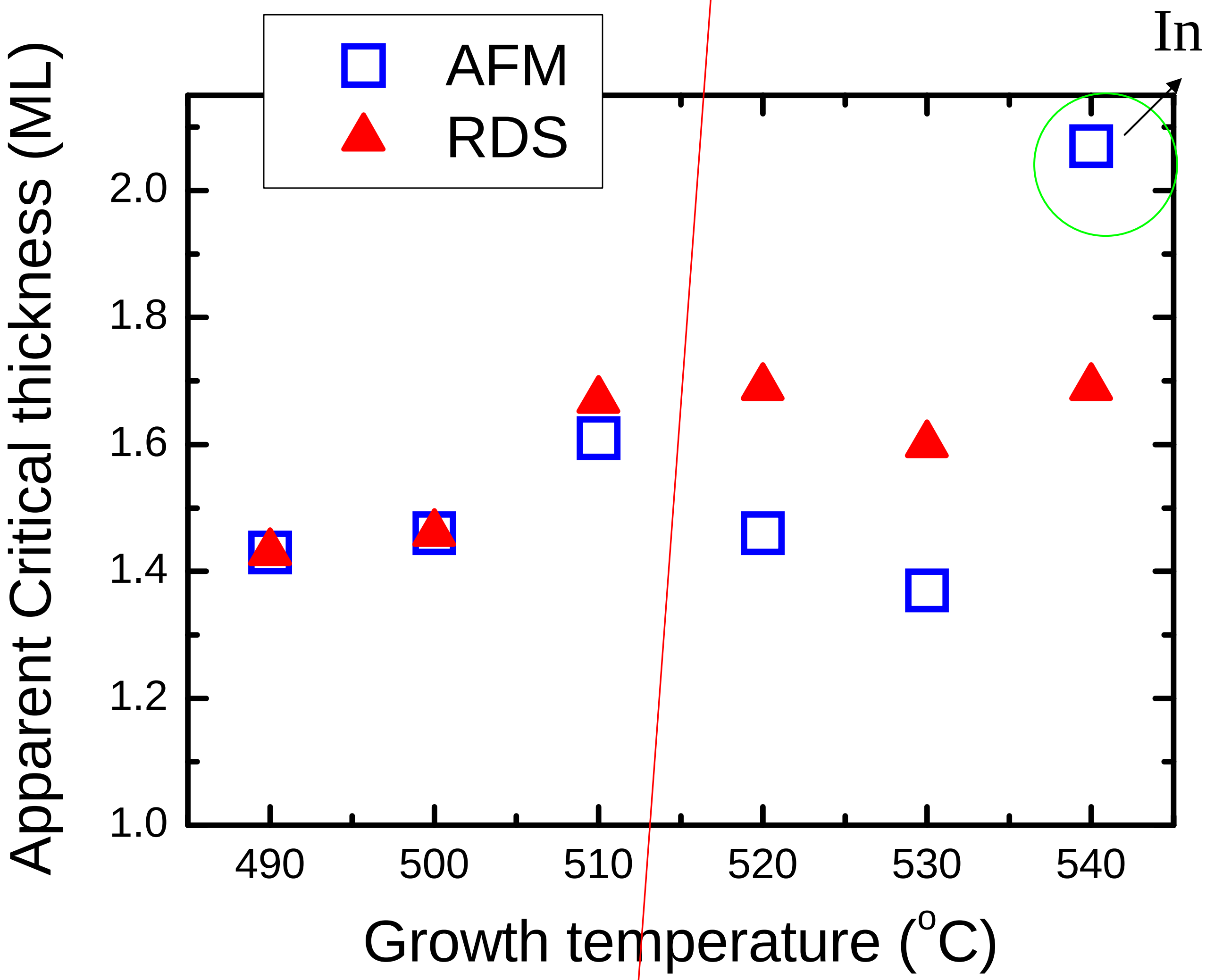
2D-3D :



Red bars: InAs becomes saturated in WL by RDS

◊ rapid change of OA, anisotropic strain in WL

2D-3D



In
AFM
RDS
Apparent Critical thickness (ML)
2.0
1.8
1.6
1.4
1.2
1.0
490
500
510
520
530
540
Growth temperature (^{o}C)

Institute of Semiconductors CAS
中国科学院半导体研究所
1960

$E\ \ (k)=E\ \ (-k)$ $E\ \ (k)=E_{\mp}(-k)$

$$\underbrace{\qquad\qquad\qquad\qquad}$$

$E\ \ (k)=E_{\mp}(k)$

☑ ☑

Zeeman

SO

$$H_{SO} = -\frac{\hbar}{4m_0^2c^2}\boldsymbol{\sigma}\cdot\boldsymbol{p}\times(\nabla V_0)$$

V_0

ω **p, k, v** $\subseteq V_0$

Lorentz

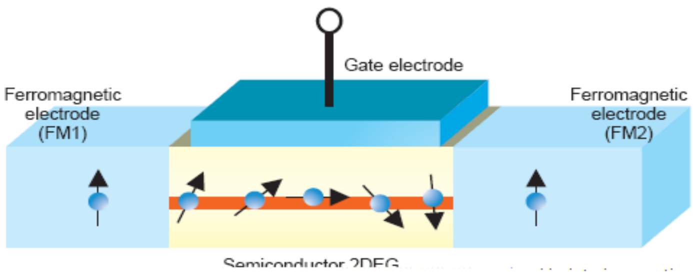
-V **E**

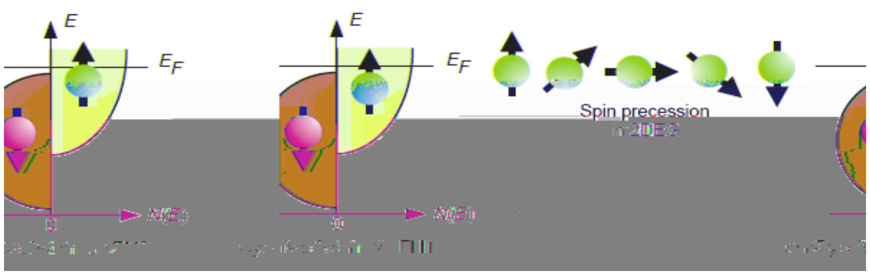
B

$$B \mid 4\frac{V}{c^2} v \Delta E$$

C_{2V}

$$H_{SO} = -\frac{\hbar}{4m_0^2c^2}\,\boldsymbol{\sigma}\cdot\boldsymbol{p}\times(\nabla V_0)$$





SO

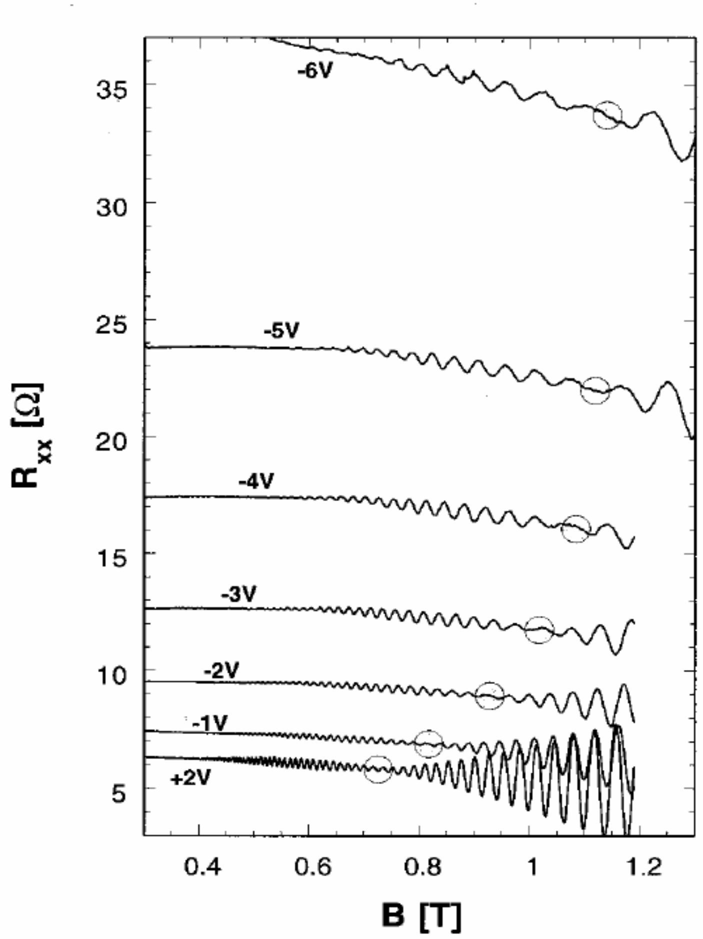
S. Datta and B. Das, Appl. Phys. Lett. 56, 665(1990)

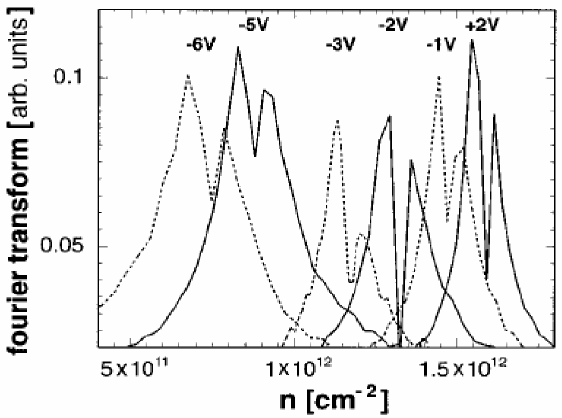
Y

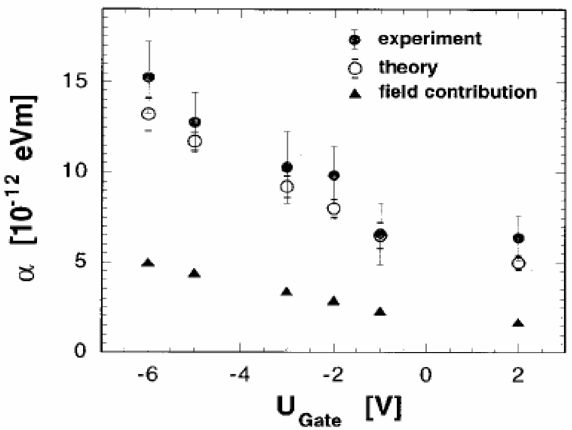
ω_z, p_x

1 (SdH)

$In_xGa_{1-x}As/InP$ 2DEG



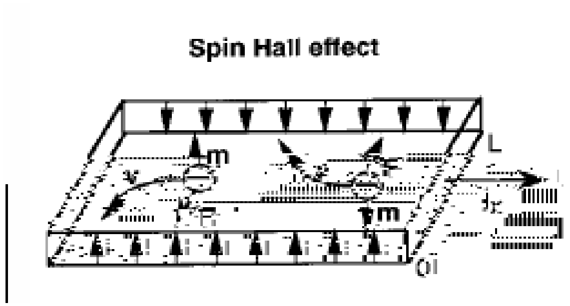




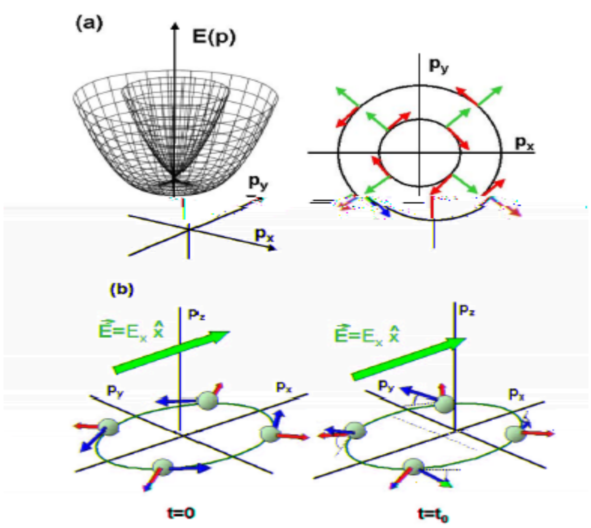
PRB55R1958(1997)

2) Hall

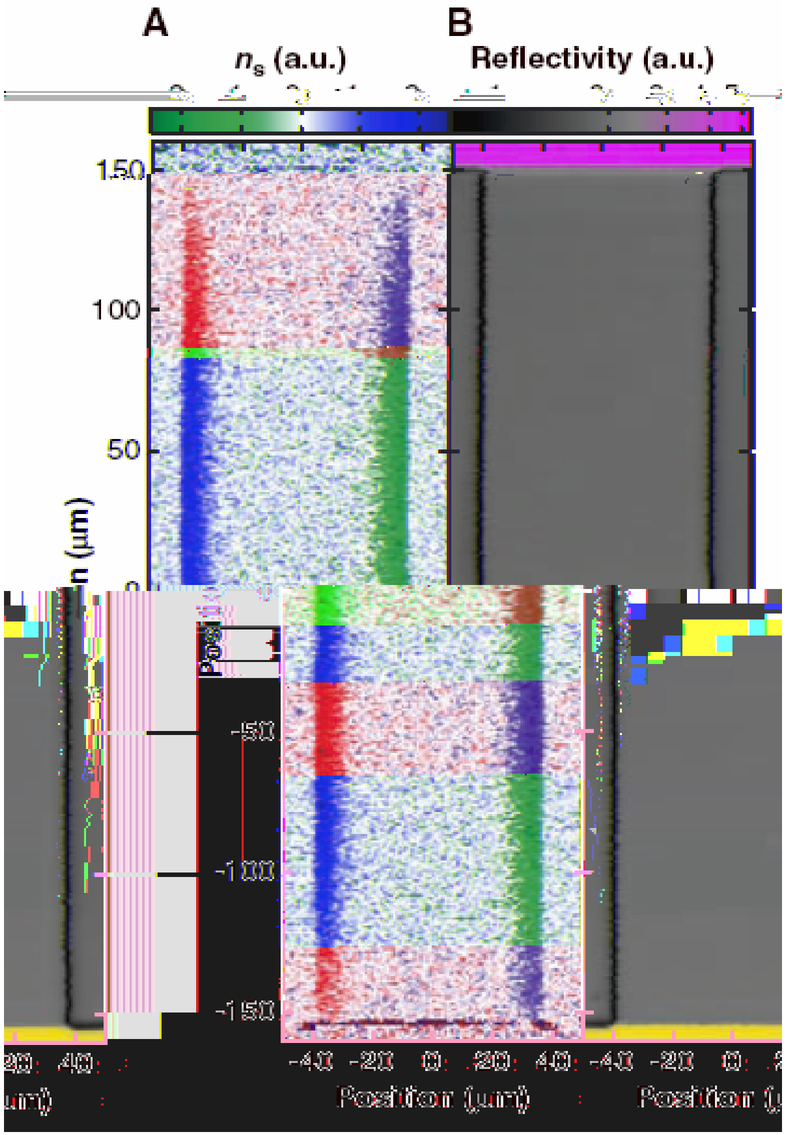
2 σm n-GaAs on AlGaAs



: Rashba

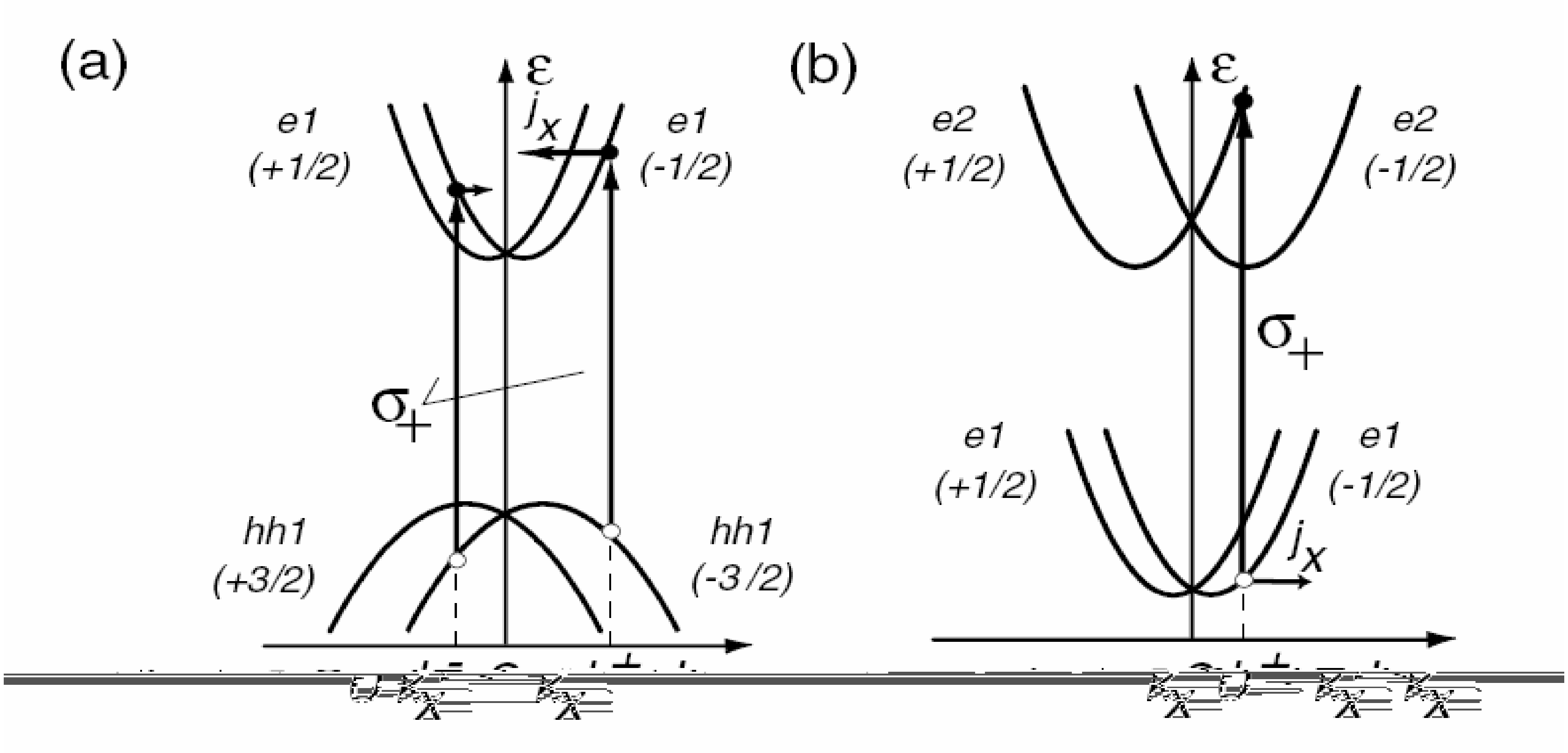


PRL92P126603(2004)



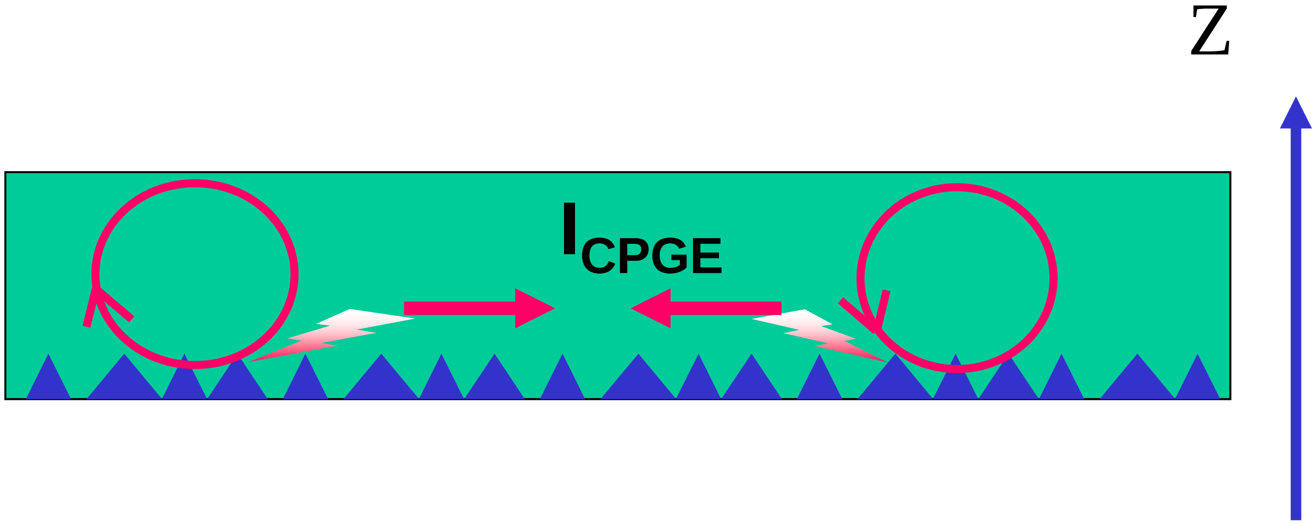
Science306-1910-2004

Circular photogalvanic effect



kx+ kx-

CPGE



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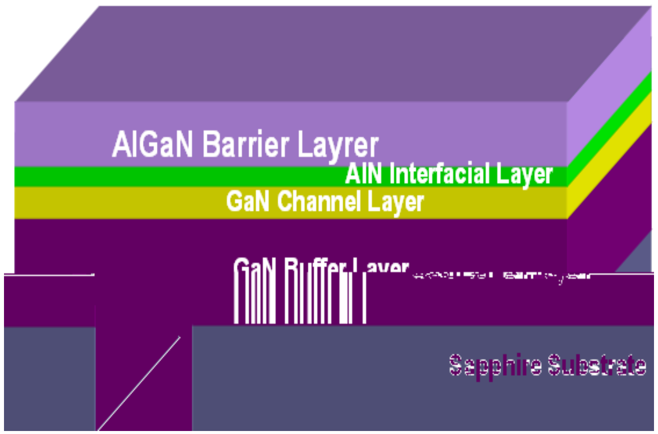
GaN/AlGaN 2DEG CPGE

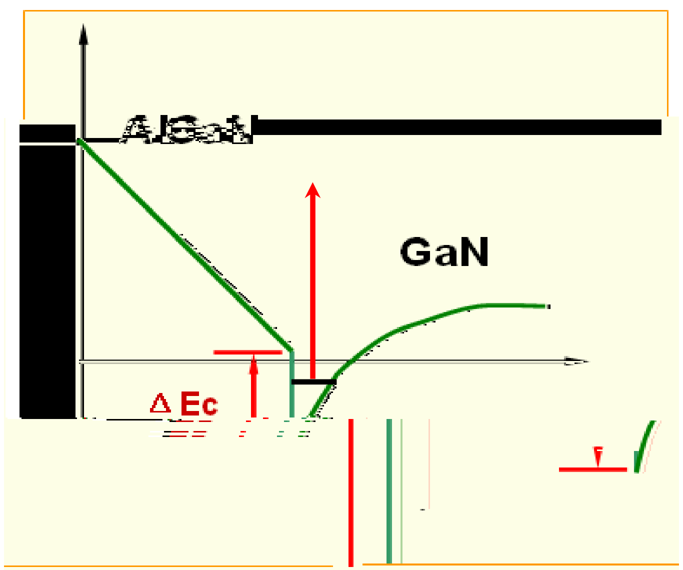
2006 APL

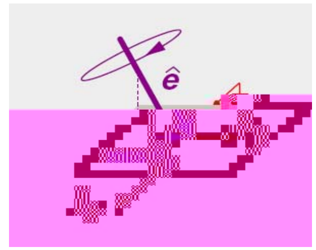
2007 APL PRL

GaAs/AlGaAs 2DEG InN InAs
InAs CPGE

GaN 2DEG CPGE

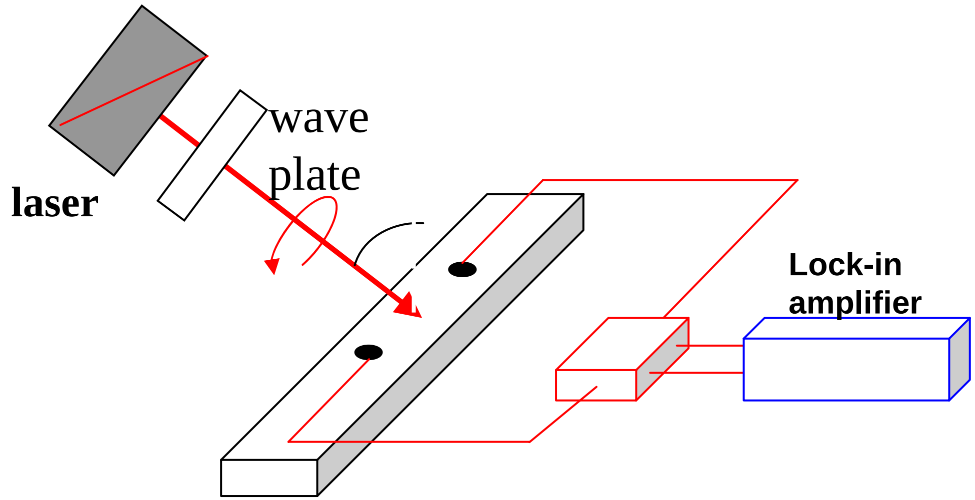






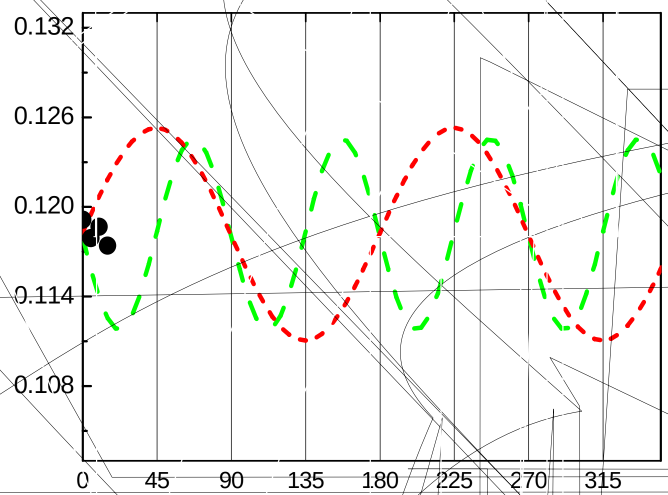
:

1060 nm (1.1 eV)



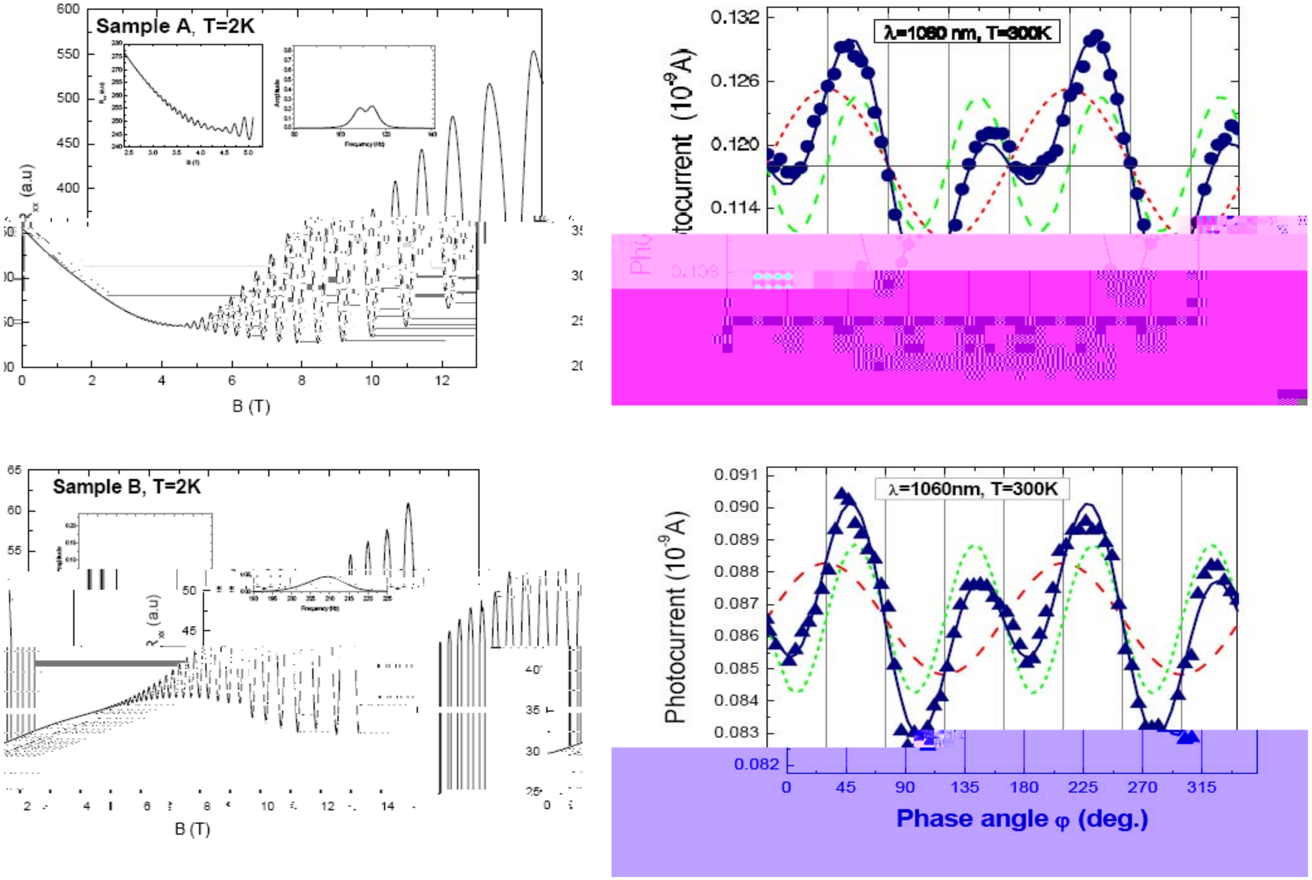
CPGE setup

GaN 2DEG CPGE



$$j_{\varsigma} \mid j_{c} \sin 2\pi\, 2\; j_{L} \sin 2\pi \cos 2\pi\, 2\; j_{0}$$

SdH CPGE



Y.Q.Tang , et al, APL, **91**, 071920 (2007)

SOC constant of BIA and SIA terms in wurtzite structure (GaN-based)

BIA SIA ?

$$\zeta \mid \frac{\hbar^2 eE}{4m^* E_g}$$

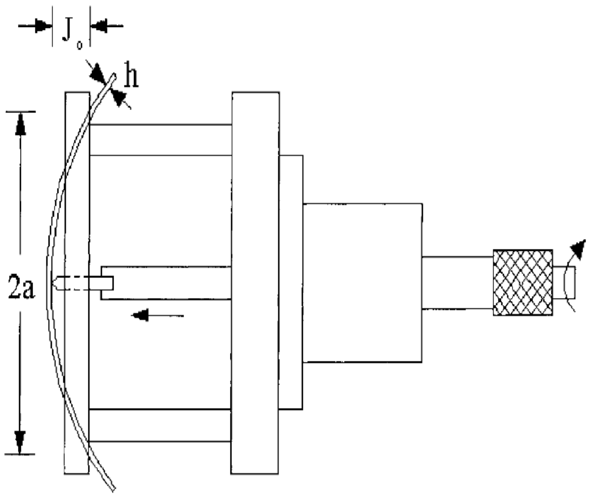
$$\zeta_S \leftarrow E_{built\,4\,in}$$

AlGaN/GaN :

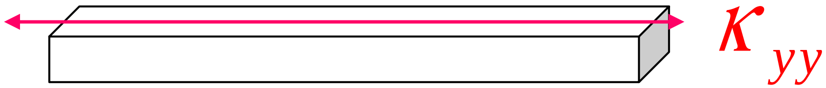
: ~ MV/cm

CPGE

Experimental setup for uniaxial strain



:



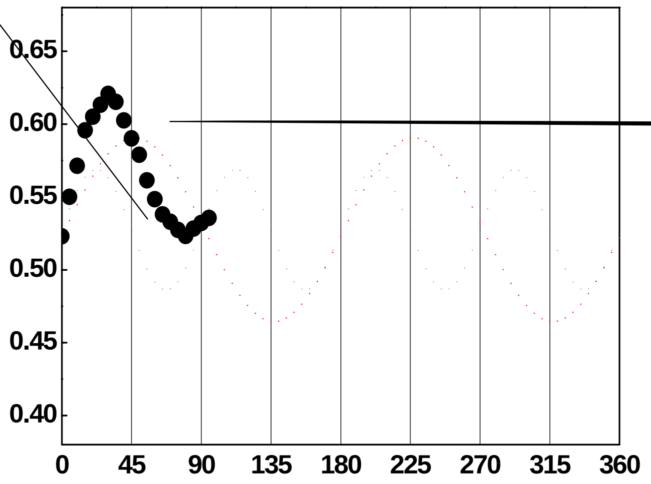
Y :

$$\kappa_{yy} \;|\; 3hJ_0 \Big/ 2a^2$$

Z :

$$\kappa_{zz} \;|\; 4\,\frac{C_{12}}{C_{13}}\,\kappa_{yy}$$

CPGE current as a function of the additional uniaxial strain



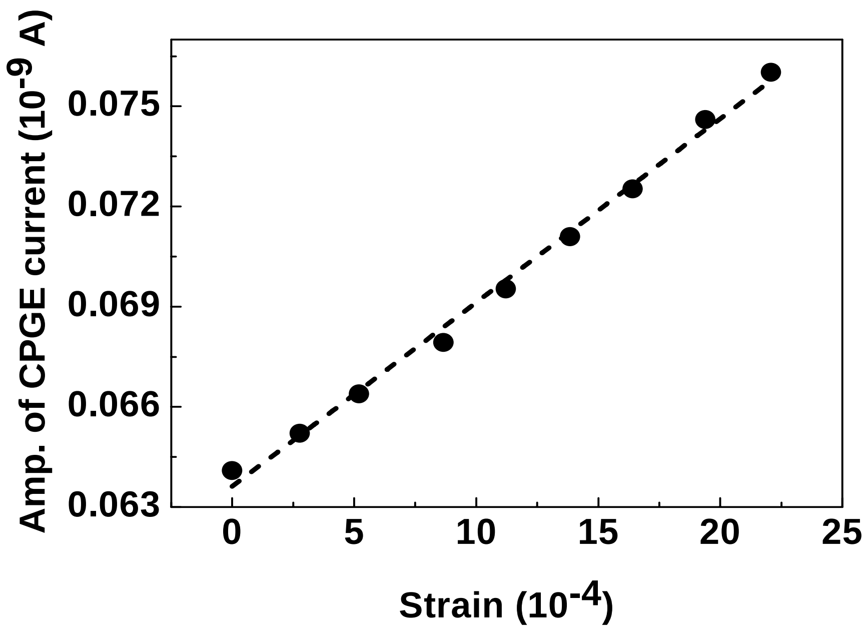
Ratio of SIA and BIA SOC constants

$$\zeta_s \leftarrow E_{built\,4\,in}$$

$$j_y(\kappa_{yy}) \mid j_b^0\, 2\, j_s^0\, 2\, k_s \kappa_{yy}$$

$$j_y \mid j_b^0\, 2\, bE_0\, 2\, bE_{un}(\kappa_{yy})$$

$$a_s / a_b \mid j_b^0 / j_s^0 - 13.2$$



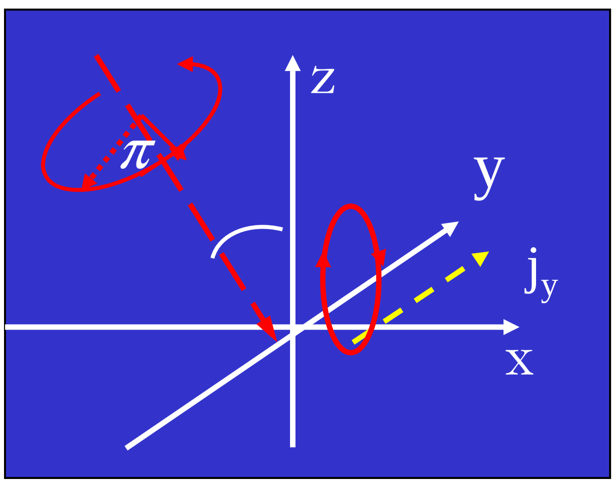
X.W.He , et al, APL, **91**, 071912 (2007)

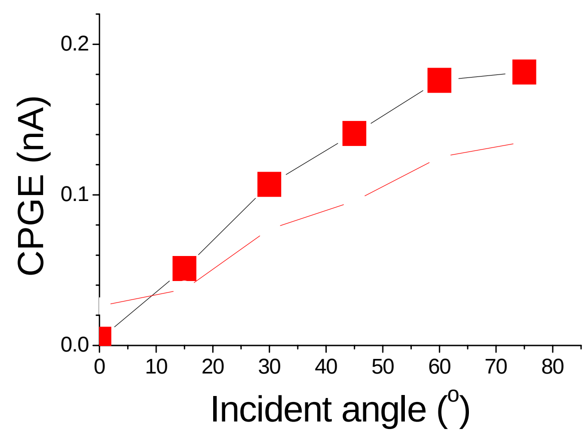
Observation of the anomalous CPGE

CPGE :

$$J_x \mid \nu_{xy} i / E \Delta E^{*} 0_y \quad \Longrightarrow \quad \sin\lambda$$

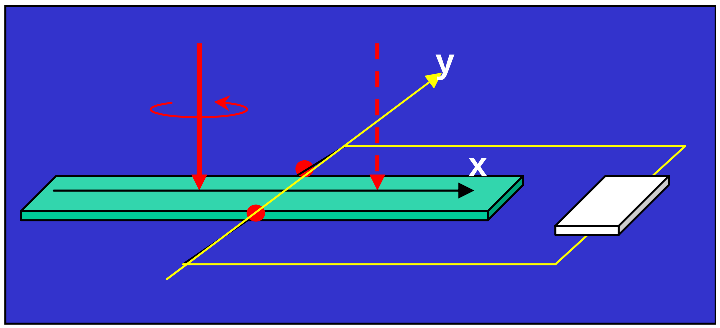
CPGE



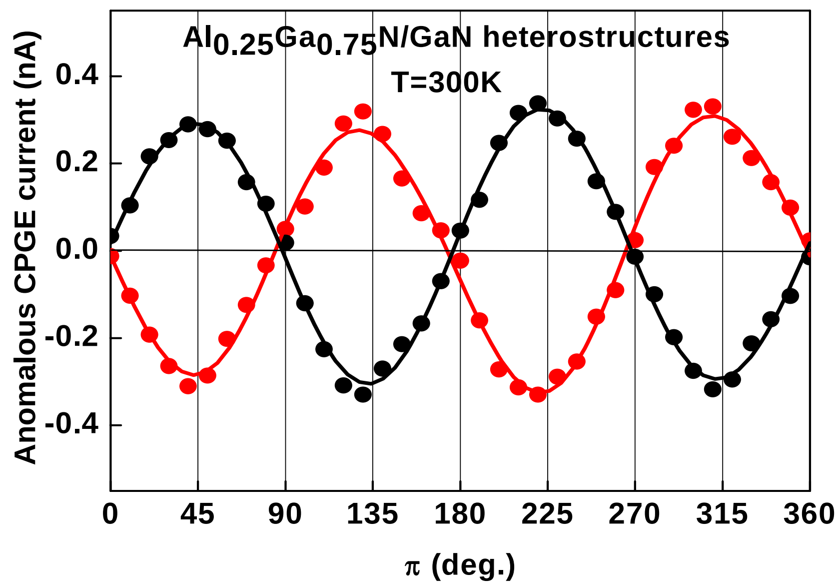


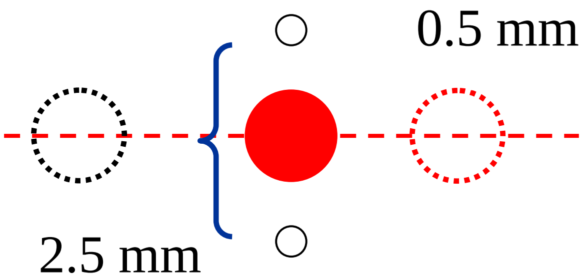
InAs CPGE

Observation of the anomalous CPGE



1.1 mm

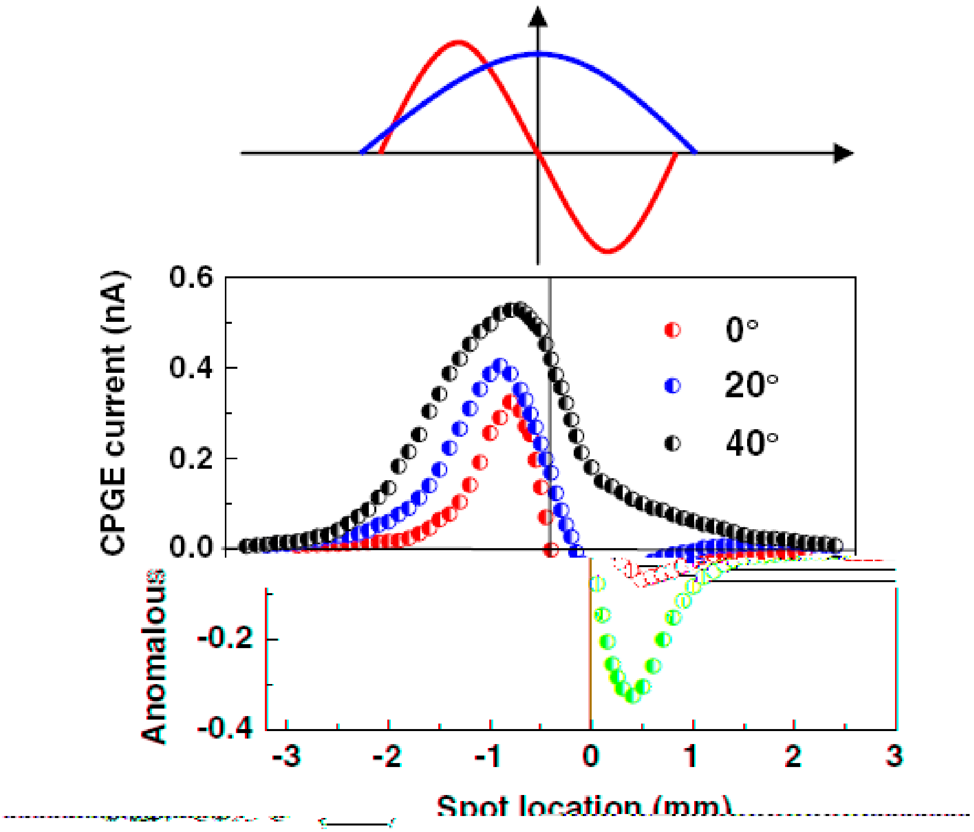




CPGE 1/4

X.W.He , et al, PRL, 101, 147402 (2008)

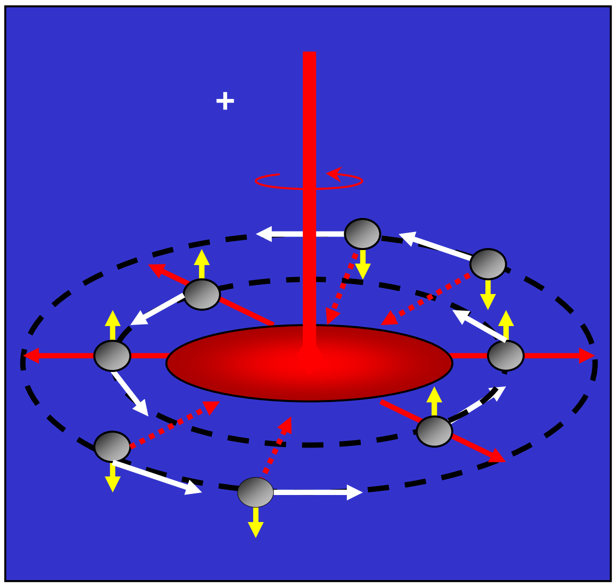
Observation of the anomalous CPGE



CPGE

X.W.He , et al, PRL, 101, 147402 (2008)

Mechanism of the anomalous CPGE



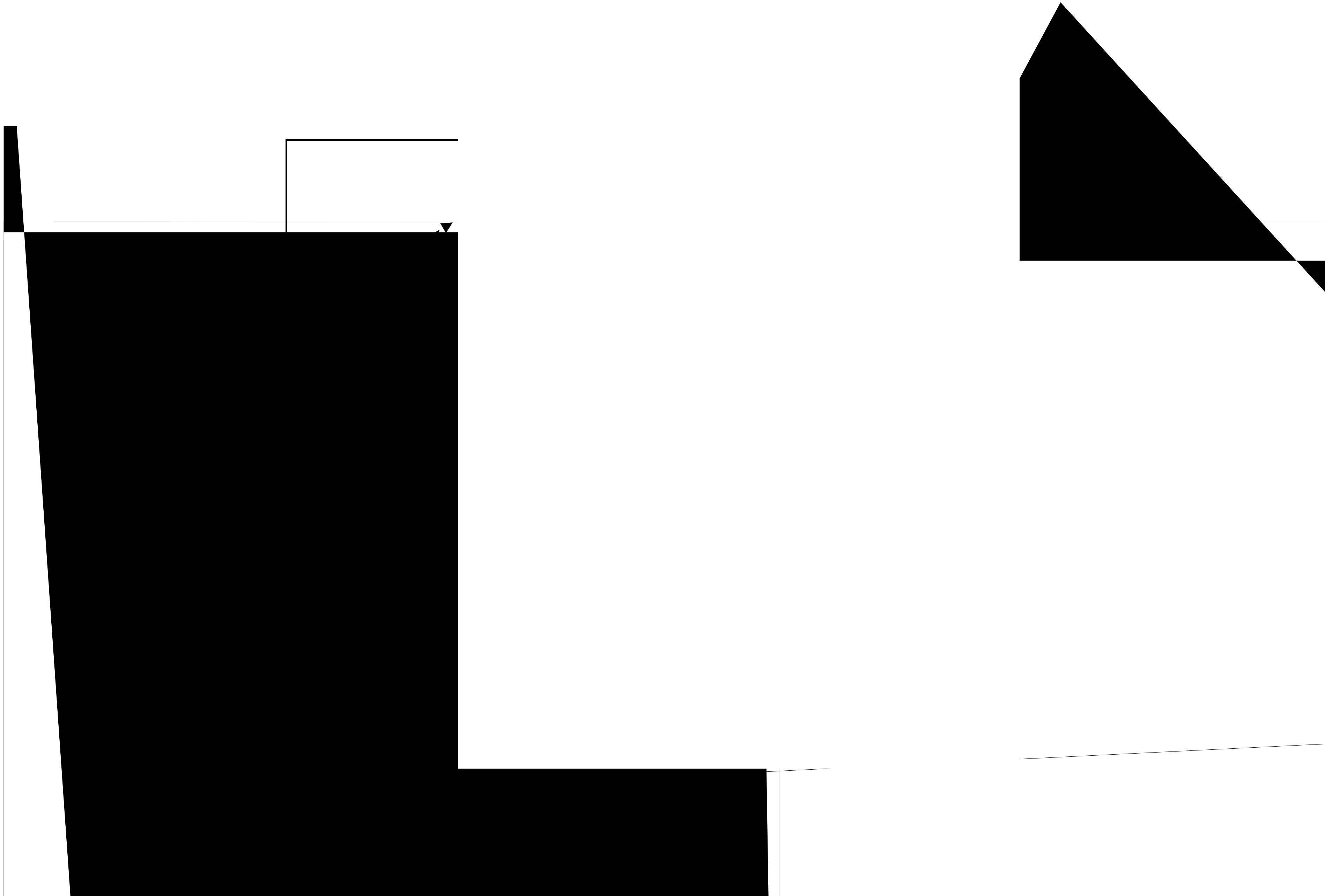
RSHE

$$u(r) \mid u_0 \exp(4\frac{r^2}{2\omega^2})$$

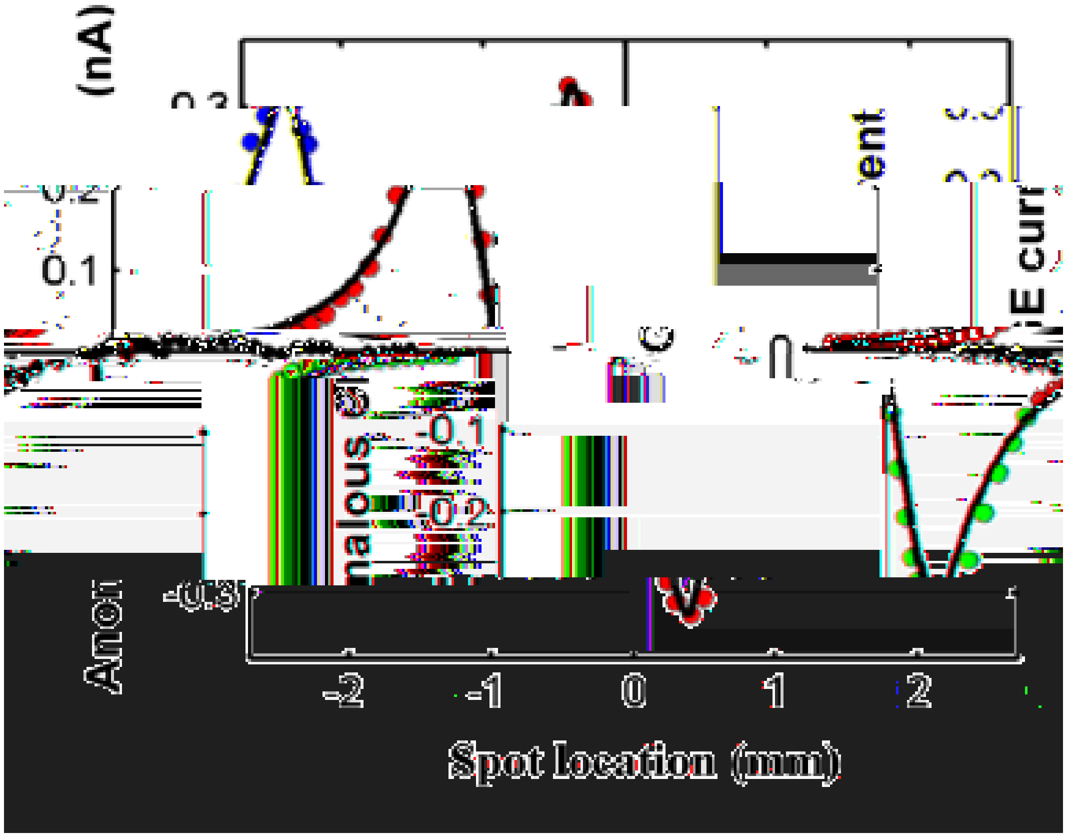
$$J(r) \mid 4J_0 \frac{r}{\omega^2} \exp(4\frac{r^2}{2\omega^2})$$

$$f(r) \mid 4 f_0 \frac{r}{\omega^2} \exp(4\frac{r^2}{2\omega^2})$$

$$J_{Hall} \mid J_0 \sin 2\pi$$



Observation of the anomalous CPGE

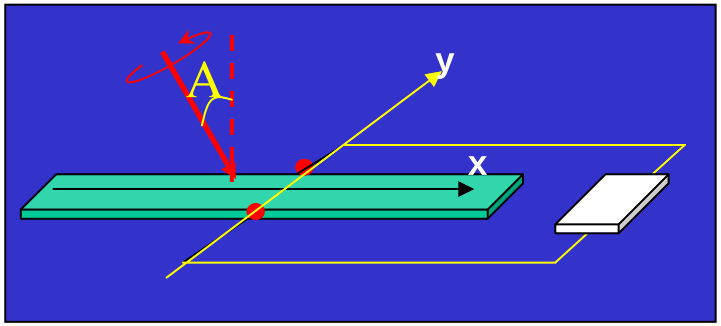


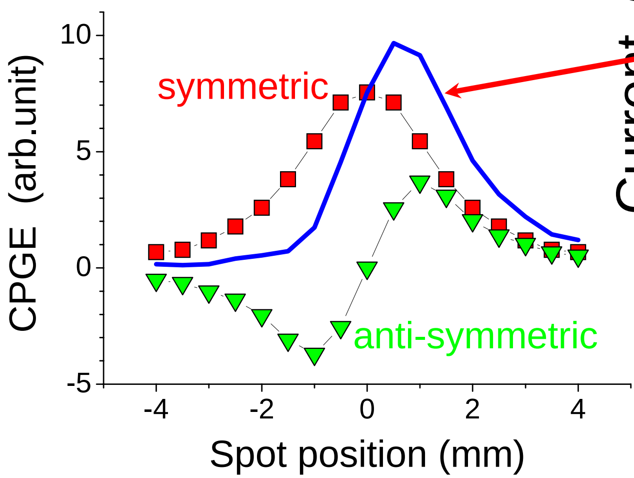
The current as a function of the light spot location with the light spot of 1.1mm and 0.1mm in diameter, respectively.

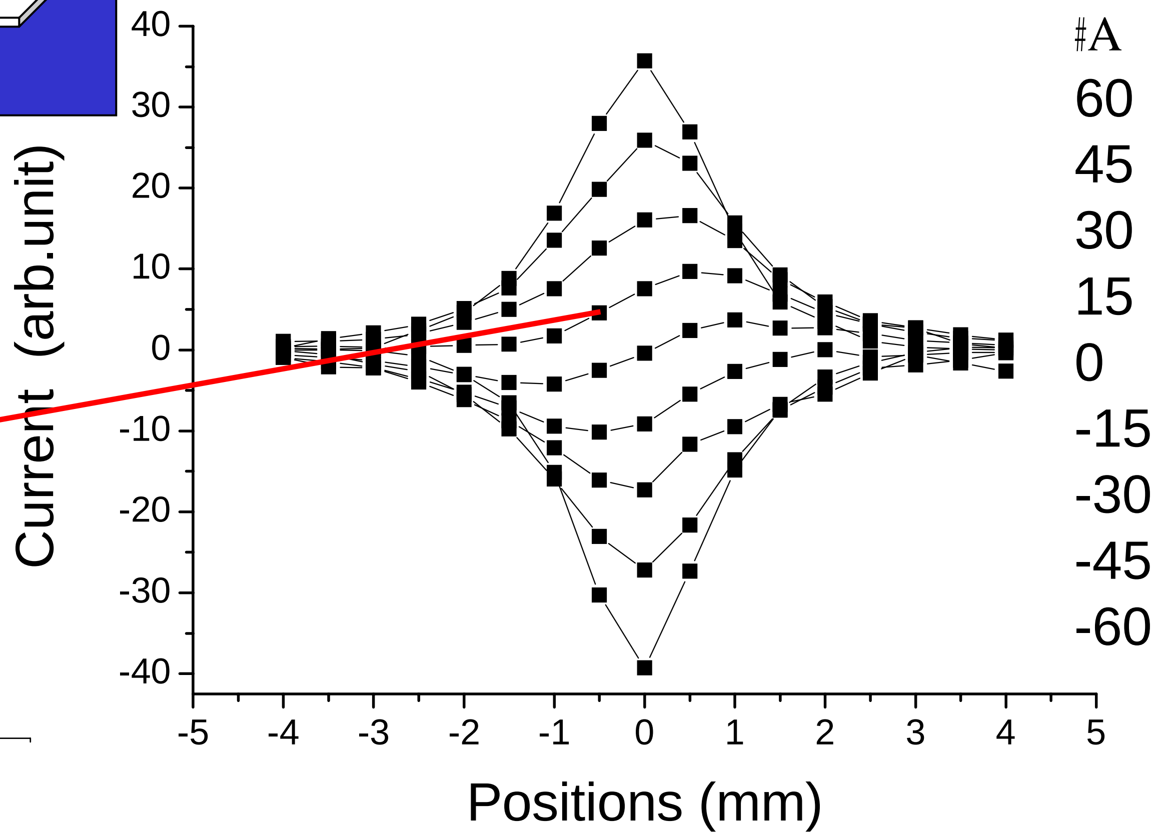
$$F \mid \frac{f_0}{q} e - 2.4\Delta 10^{419} N$$

X.W.He, et al, PRL, 101, 147402 (2008)

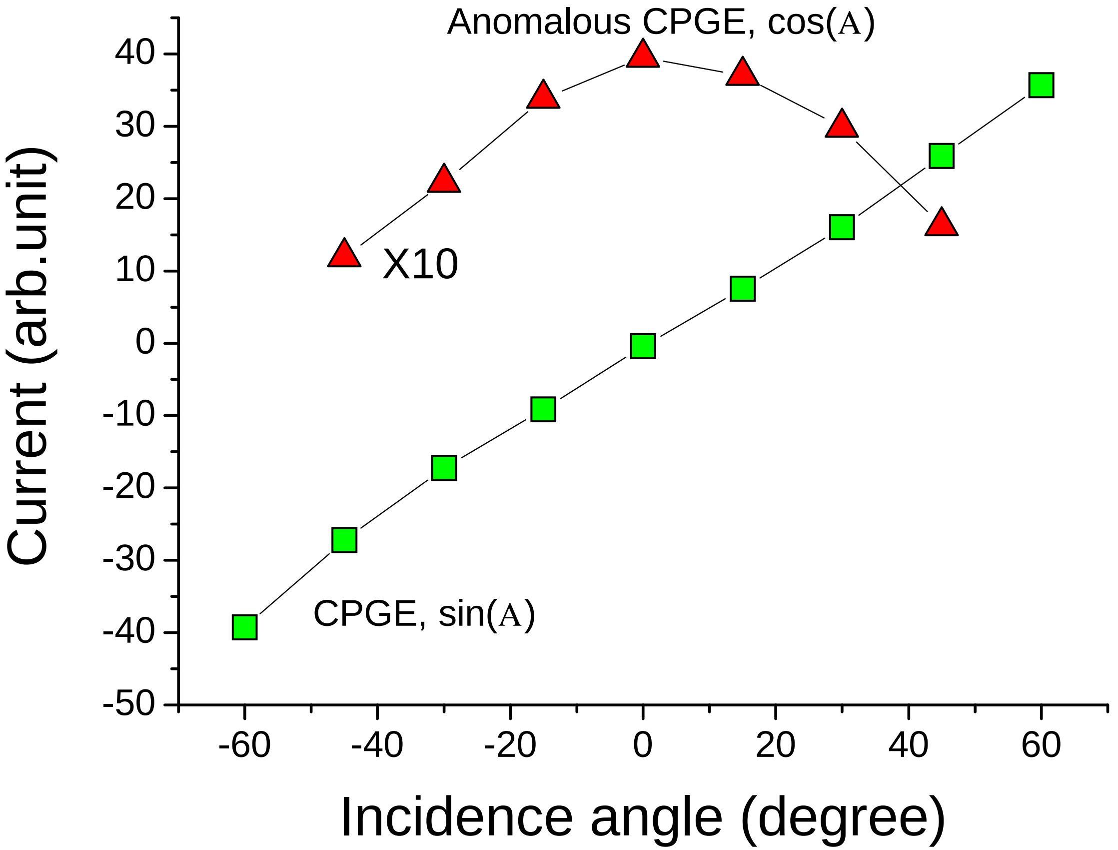
Anomalous CPGE in GaAs/AlGaAs 2DEG







Anomalous CPGE in GaAs/AlGaAs 2DEG



CPGE

CPGE

1

2 QW

RDS

RDS

3

4 RDS

Institute of Semiconductors CAS

1960