Recent Status of Polarized Electron Sources at Nagoya University

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Topics

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Photocathode R&D

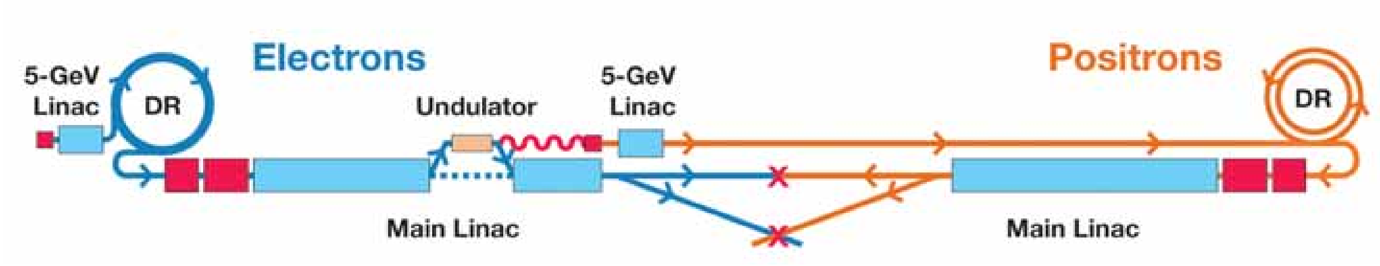
- Field emission of spin-polarized electron extracted from GaAs tips

Emittance of NEA photocathode

- Initial emittance comparing with bulk-GaAs and GaAs-GaAsP superlattice

Research Purpose of PES

- Polarized Electron Source (PES)
  - Necessary for high energy physics
    - Linier collider project (ILC project)



  - Powerful application for material sciences
    - Spin-polarized electron microscopy

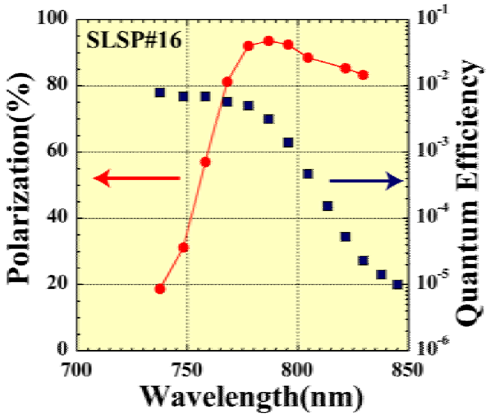
      e.g. SPLEEM (Spin-Polarized Low Energy Electron Microscope)

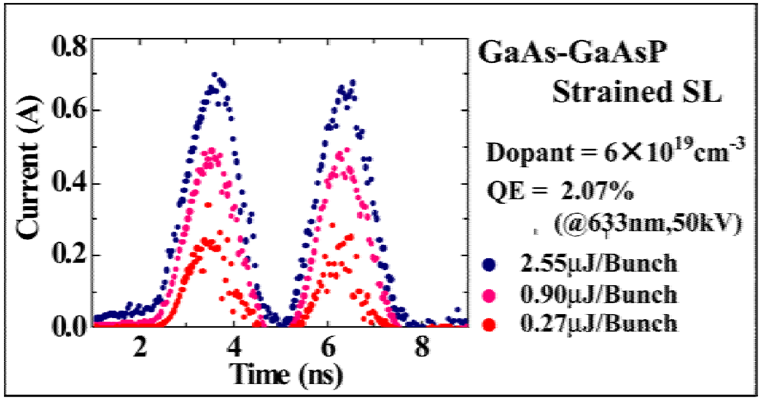
    - Surface Analysis (SPEELS, SPIPES)
    - Electron beam holography

      considering with spin effect

Topic 1: Photocathode R&D

- Photocathode developments
  by GaAs-GaAsP strained superlatttice
  - Polarization ~90% @ QE 0.5%
  - Generation of multi-bunch beam (by overcoming SCL effect)





- Few problems are still remained for photocathode
  Low emittance and long life time of photocathode

1. Low Emittance and High Brightness Polarized e^- beam
2. Extraction of Polarized e^- beam without NEA surface problem

Method

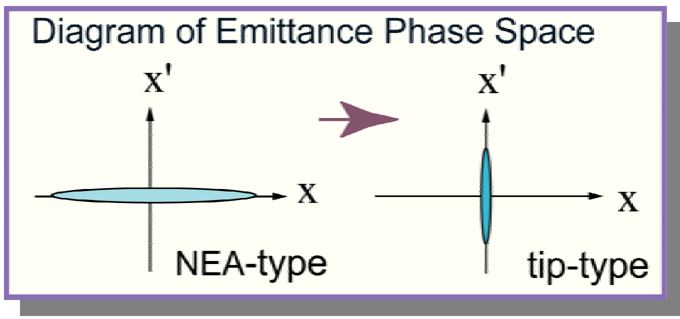
1. Low emittance spin polarized electron

i) spin polarization

→ GaAs type semiconductor

ii) low emittance

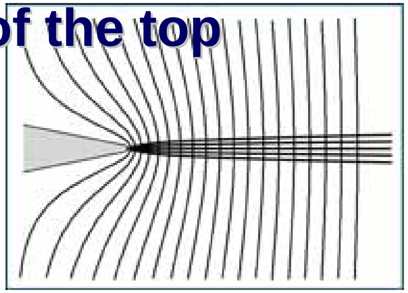
→ cross section of beam: very small



Using tip-GaAs

(the feature is needle like)

Field emission from very small area of the top



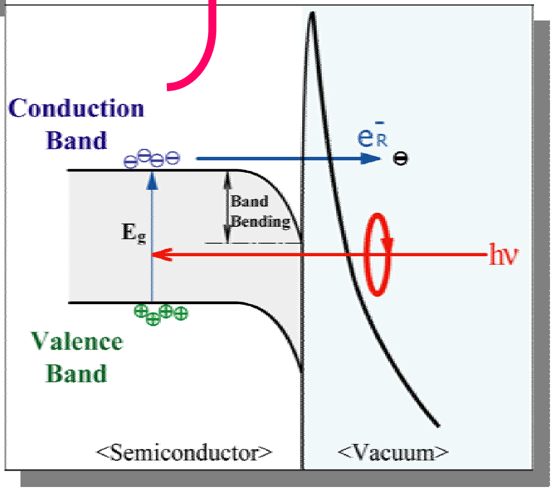
2. NEA surface lifetime problem

(by avoiding NEA surface)

Using a tunneling effect

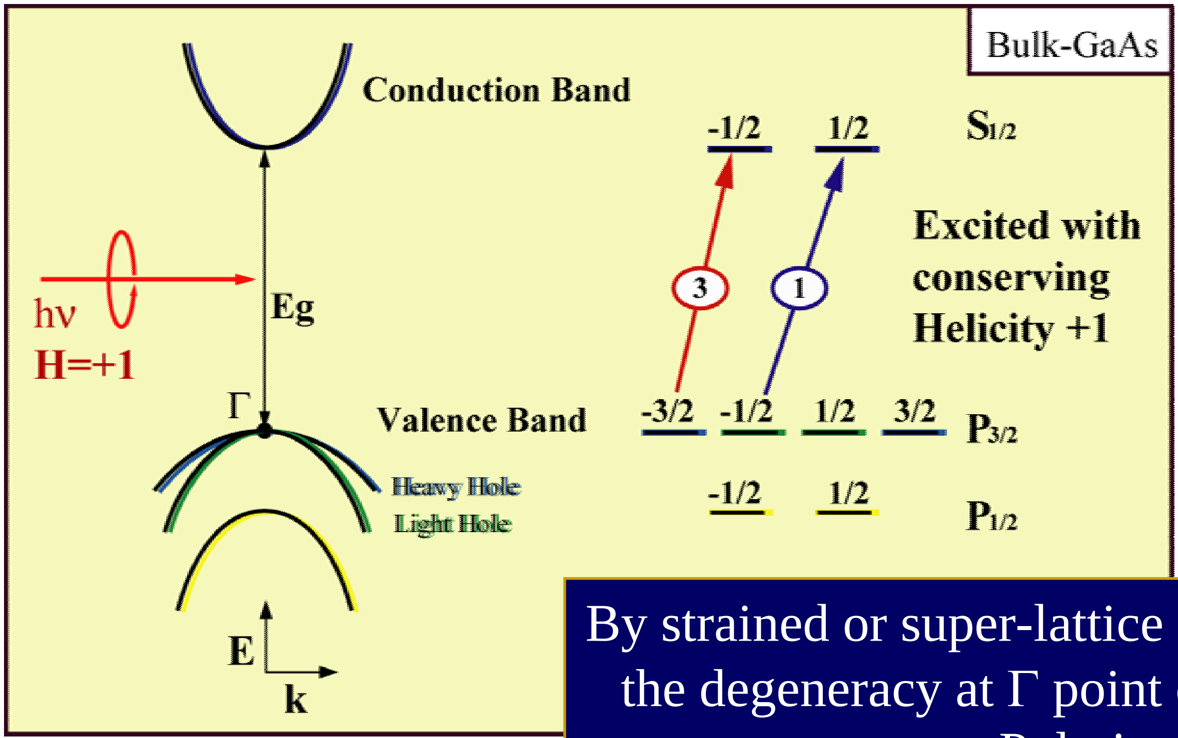
by a high gradient at the surface

→ Field Emission



Method

- Basis of generation of polarized electron beam using semiconductor photocathode.



Under illuminating circular light to GaAs semiconductor.

Selective excitation from valence band to conduction band.
(conserving the helicity)

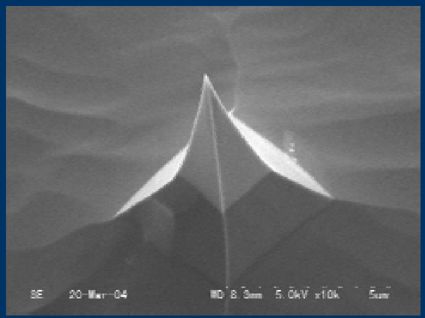
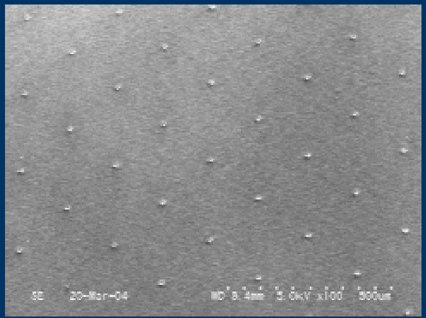
Bulk-GaAs has degeneracy of electron bands at Γ.
Polarization: max. 50%

By strained or super-lattice structure GaAs,
the degeneracy at Γ point can be separated,
Polarization > 50% enable
In fact, Polarization ~ 90%
by strained supper-lattice structure

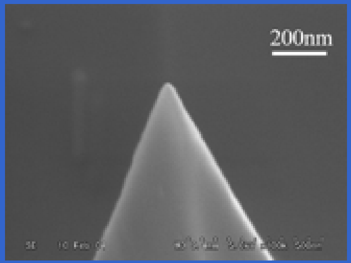
Photocathode

- Photocathode sample (tip-GaAs)

(p-GaAs substrate, Zn-dope:2 $\times 10^{19} cm^{-3}$)

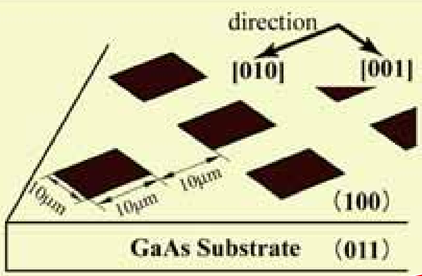
SEM images (left:×25k, right:×100)



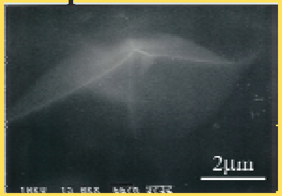
Height :~10μm
Radius :~25nm

- Fabrication of tip-GaAs

①Fabricate a Pattern Mask using Photo-lithography
②H_3PO_4 Wet Etching (Anisotoropic Etching)

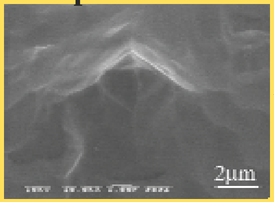


$H_3PO_4:H_2O_2:H_2O$=10:1:1
Temperature 20℃

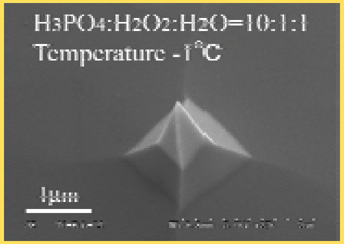


temperature↑

$H_3PO_4:H_2O_2:H_2O$=5:1:1
Temperature -1℃



ratio ←



H_3PO_4 etching solution's condition, mixing ratio and temperature

Apparatus

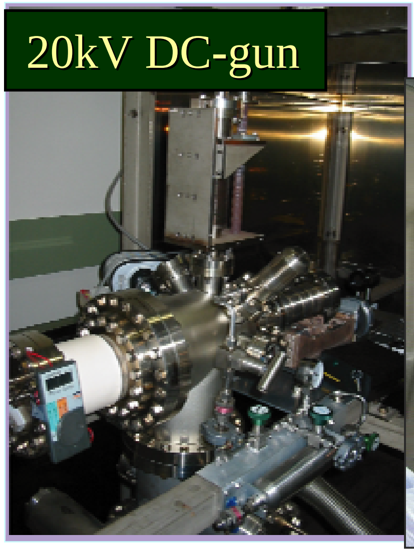
Electron gun

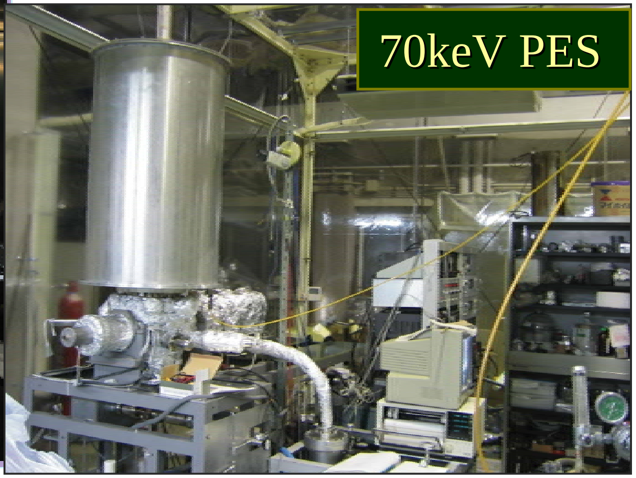
- **70keV PES** **(I-V characteristics and polarization measurement)**

  Mott-scattering polarization analyzer
  Vacuum pressure : $3\times10^{-11}\,Torr$
  Field gradient at photocathode：0.6MV/m @70kV

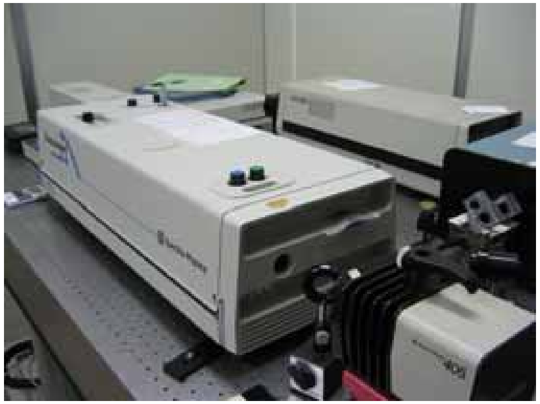
- **20kV DC-gun** **(I-V characteristics)**

  20kV-DCgun, variable gap separation
  Field gradient at photocathode ~ 4.8MV/m (@20kV, gap=3.2mm)





Laser



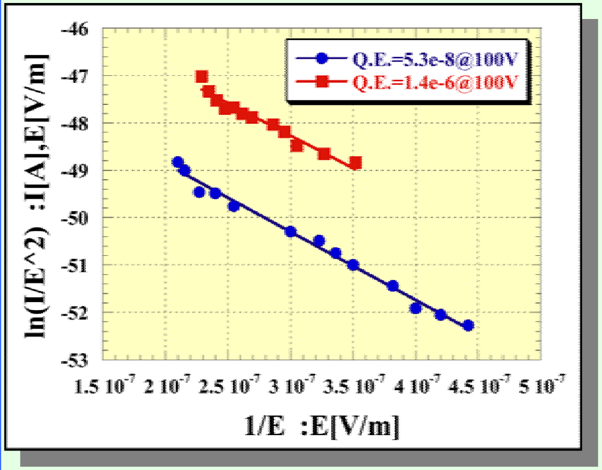
Ti:Sapphire Laser

Model3900 (Sp) CW-Laser (532nm, 5W seed)	
Wavelength	730nm〜950nm

Tsunami (SP) Pulse-Laser (532nm, 5W seed)	
wavelength	730nm〜850nm
Pulse width	〜 20 ps
repetition	81.25 MHz

Experimental results (1) I-V characteristics

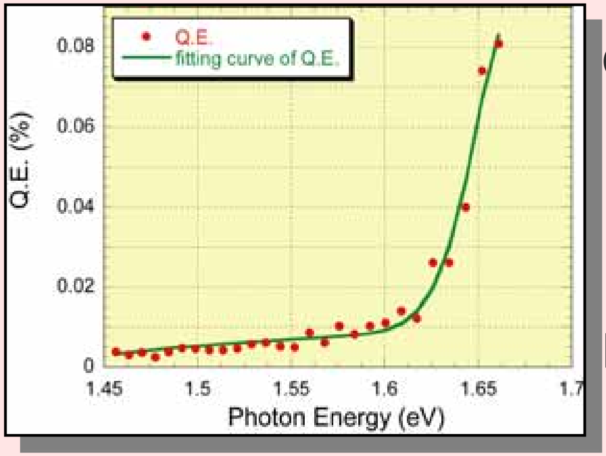
- Behaviors ; under impressing high gradient and illuminating circular light



I-V characteristic
→ F-N(Fowler-Nordheim) plot

Tunneling effect through a surface barrier (Field emission)

Not observe by GaAs without tip



QE vs. Photon energy at high gradient field (E=3.4MV/m @ Flat)

well fit

Fitting curve is estimated by WKB approximation.

Demonstrated the tunneling yield depending on an excitation energy.

Field-Emission is observed

Photon-excited electrons were extracted by F.E.mechanism

Estimation of electron affinity χ

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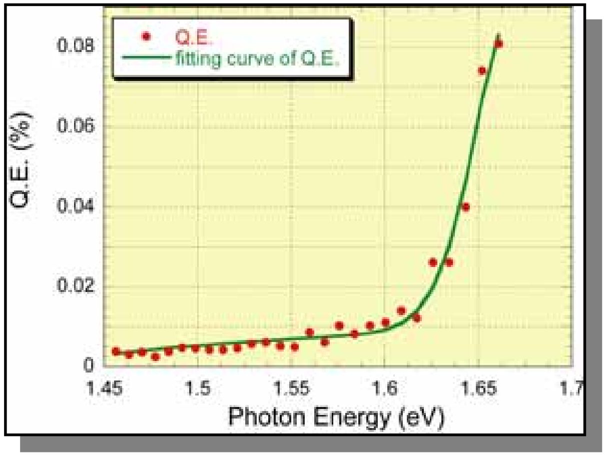
[Estimation of χ by the QE–λ data]



Assumption: proportional to a tunneling yield of surface barrier

Tunneling yield T (WKB approximation) is written by

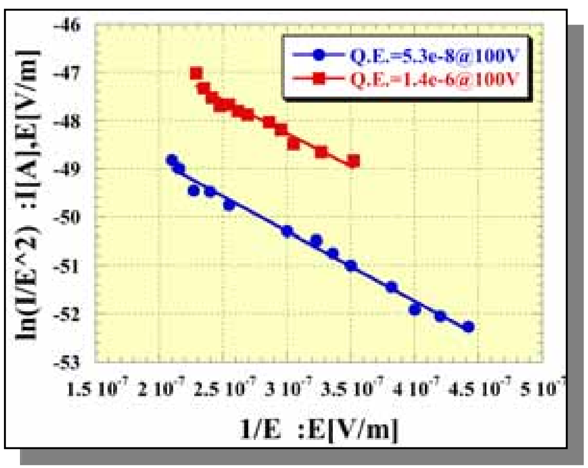
$$T(\varepsilon_z) \propto \exp\left[-\frac{4\sqrt{2m}}{3\hbar eE}(\chi - \varepsilon_z)^{3/2} \right]$$

The solid line is obtained by least-squares fitting in left figure.

Therefore, χ is estimated as

$$\chi = 1.710 - 1.428 \rightarrow \mathbf{0.23 \pm 0.01\,eV}$$

[Estimation of χ by F-N plot data]



F-N plot is written as, **←Fowler-Nordheim equation**

$$\ln\left(\frac{I}{E^2}\right) = -6.85\times10^9\,\frac{\phi^{3/2}}{\beta E} + \ln\left(\frac{1.54\times10^{-6}}{\phi}\right) + 2\ln\beta + \ln S$$

By the gradient of F-N plot

$$\chi = 1.64 \times 10^{-2}\,\beta^{2/3}$$

Here, assumed that field enhancement factor is 66 (calculated by POISSON) for the tip feature (curvature is 50nm, distance is 200mm)

$$\rightarrow \mathbf{0.26 \pm 0.08\,eV}$$

Consistent with each result

Experimental results (2) Spin Polarization

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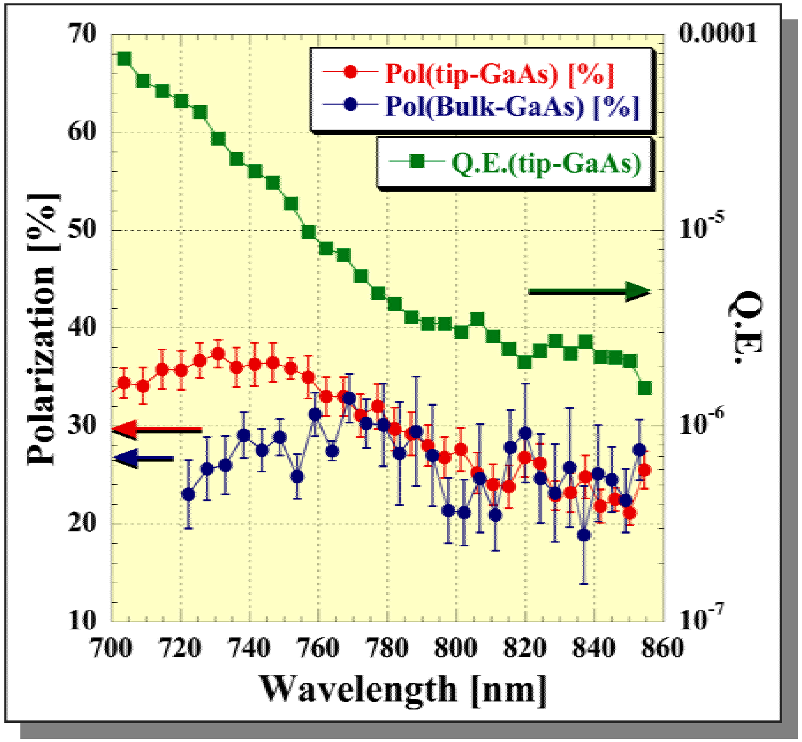
- Polarization of tip-GaAs



ESP and QE spectrum under irradiating circular light. In order to compare, NEA/Bulk-GaAs polarization is also drawn.

1) Polarization : 20〜40%

≧Bulk-GaAs' Polarization

2) tip-GaAs Polarization was higher than NEA/Bulk-GaAs' at shorter wavelength

λ < 760nm (1.6eV)

Corresponding with the rising edge of Q.E.

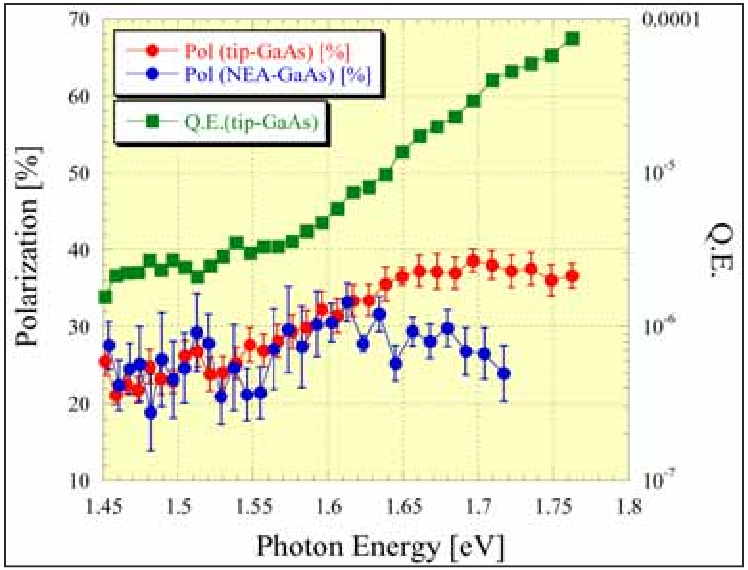
The results suggests that spin polarized electrons can be extracted by field emission mechanism

Spin polarization did not get worse,

while F.E. mechanism was substituted for NEA

Difference of each polarization

- Difference in generation process between NEA and FE
  ⇒ process of extracting into a vacuum

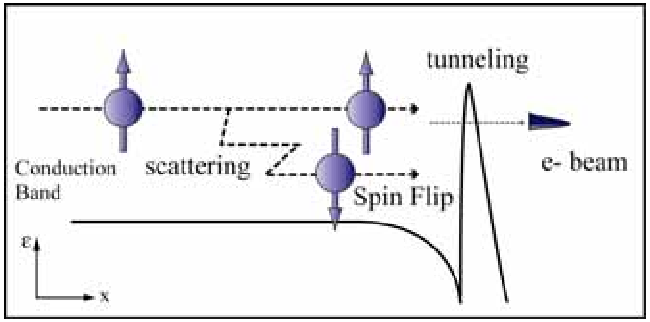


- Dependent on excitation energy (Phenomena of hot-electron)

@ **hν > 36 meV**

① Scattering in drifting process
LO phonon scattering is mainly

② Spin flip in scattering
DP-process is main process for hot e⁻



Spin relaxation time becomes smaller with rising electron energy

$$P \sim P_0 \exp\left[-\frac{\tau_{E0}}{2\tau_{s0}}\left((\varepsilon/\varepsilon_0)^2 - 1\right)\right]$$

Difference of each polarization

- Process in extracting into vacuum
  - Tunneling yield is sensitive to the excitation energy

drifting electron： $T(\varepsilon_Z) \propto \exp\left[-(\chi-\varepsilon_Z)^{3/2}\right]$

Energy dispersion becomes wider in transport process by some scattering.

Polarization of higher energy part : High polarization

lower energy part : Low polarization (cause by scattering)

High energy part is mainly extracted into vacuum.
–>Polarization becomes higher (cut off of depolarization part)

Surface tunneling is like a filter effect of polarization.

Higher energy part of electrons can be extracted dominantly.
Δε : narrow, Pol : high

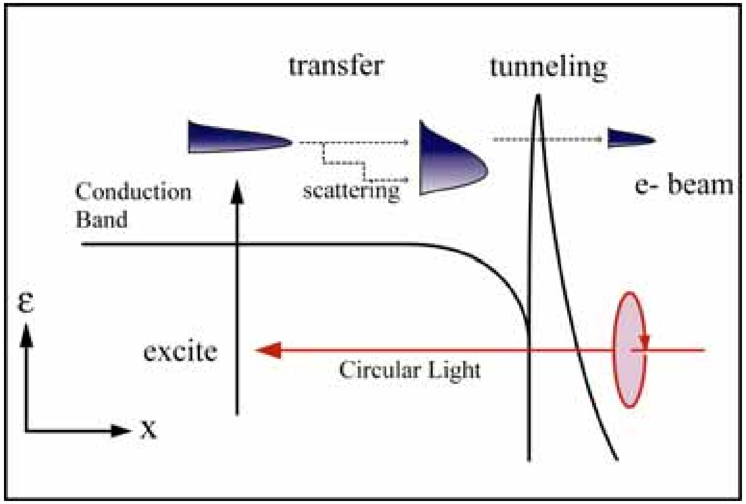


Fig. Generation process of spin polarized electrons with field emission. Blue color density means value of spin polarization.

Summary of GaAs tip photocathode

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- ***Achievements*** : We demonstrated that F.E. can be used for PES as a substitute for using NEA surface.
  - **Extraction of polarized electrons by F.E. : O.K.**
  - **Electrons extracted by F.E. have higher polarization than NEA's.**
  - **Lifetime (long lifetime compared with NEA surface (NEA~1week → F.E.>1month)**
- ***Problem*** : Work function, fine structure, surface contamination
  - **Stability and uniformity of current**
  - **Field emission characteristic** (operation voltage, field enhancement)
  - **Extract more high current (melting of the top of tips)**

We can confirm that spin polarized electrons can be extracted by F.E. , and demonstrate the fundamental characteristics.

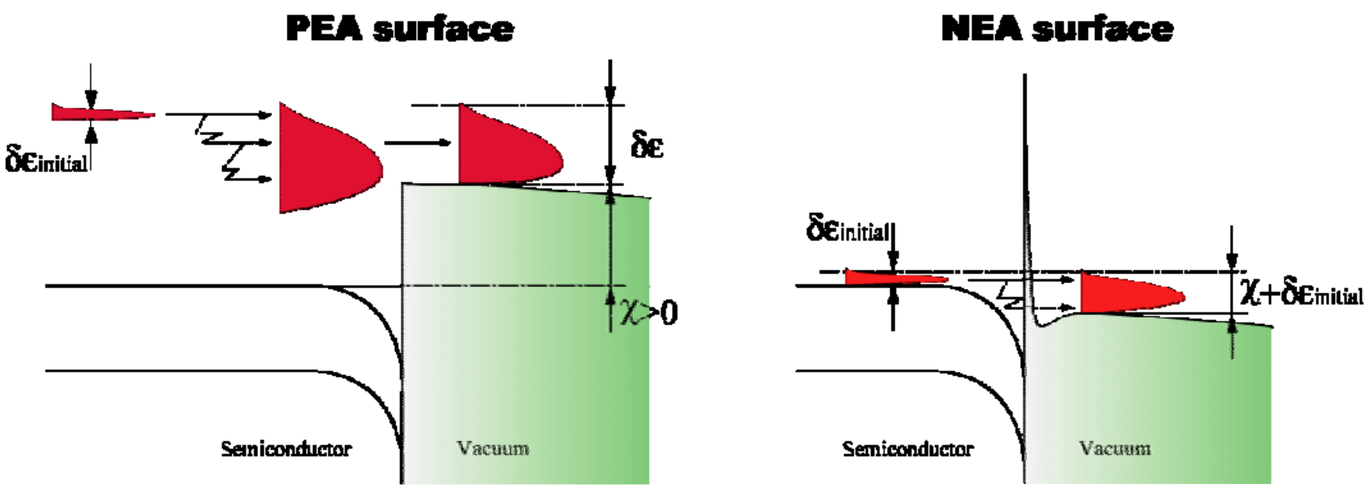
Ref. ; M. Kuwahara, *et al.*: Jpn. J. Appl. Phys. Vol. 45, No. 8A (2006) pp. 6245-6249.

Topic 2: Emittance of NEA photocathode

- Introduction
  - NEA photocathode is expected to generate a very low emittance.

    Comparing with bulk-GaAs and GaAs-GaAsP superlattice
    - Dependence of electron beam energy, excitation energy and QE.

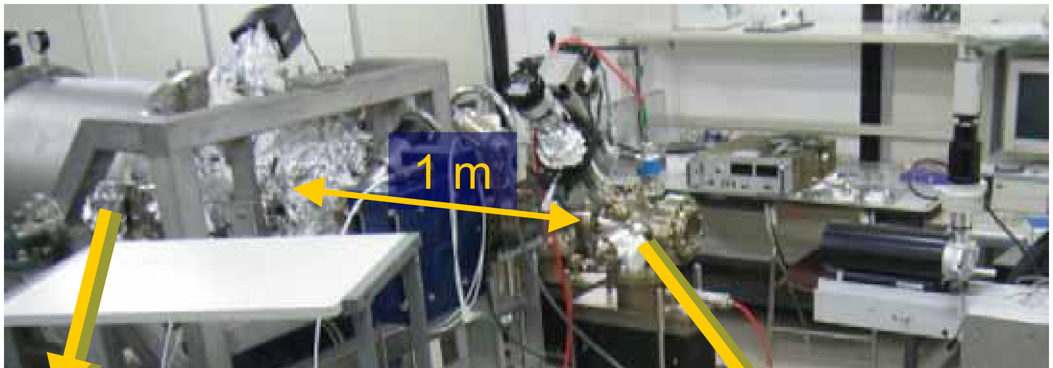
➡ We obtained the result which the emittance of beam with very low electron charge were almost 0.1 πmm.mrad.

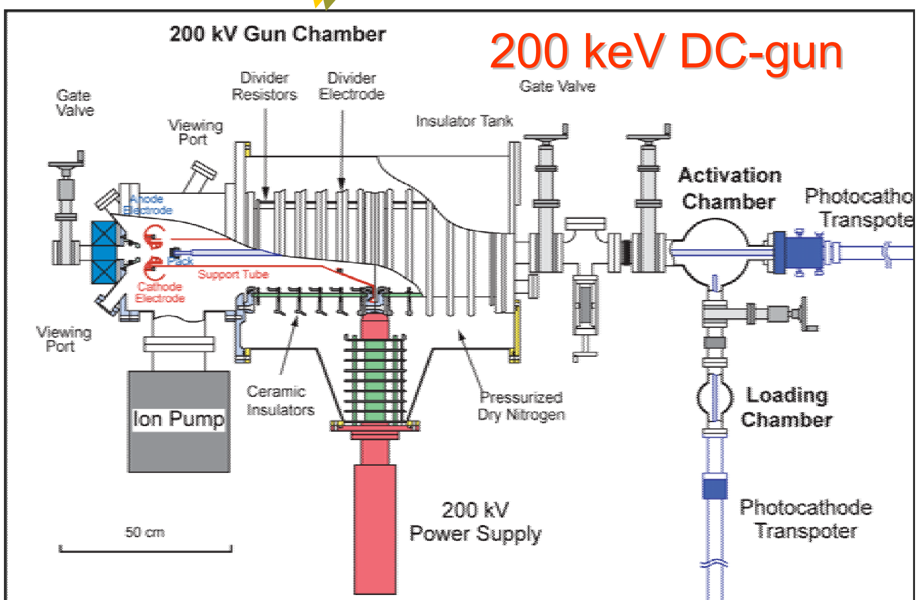


NEA photocathode is expected to generate very low initial emittance beam with high QE.

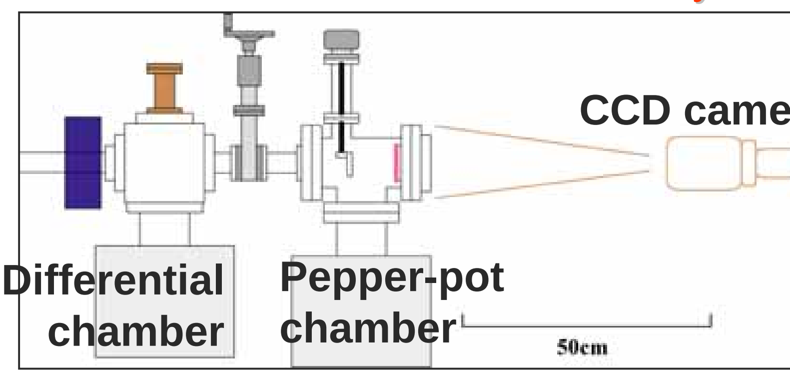
Measurement Setup

- Emittance Measurement System





Emittance measurement system



1 m drift space from 200 keV DC-gun to pepper-pot mask

Measurement Setup

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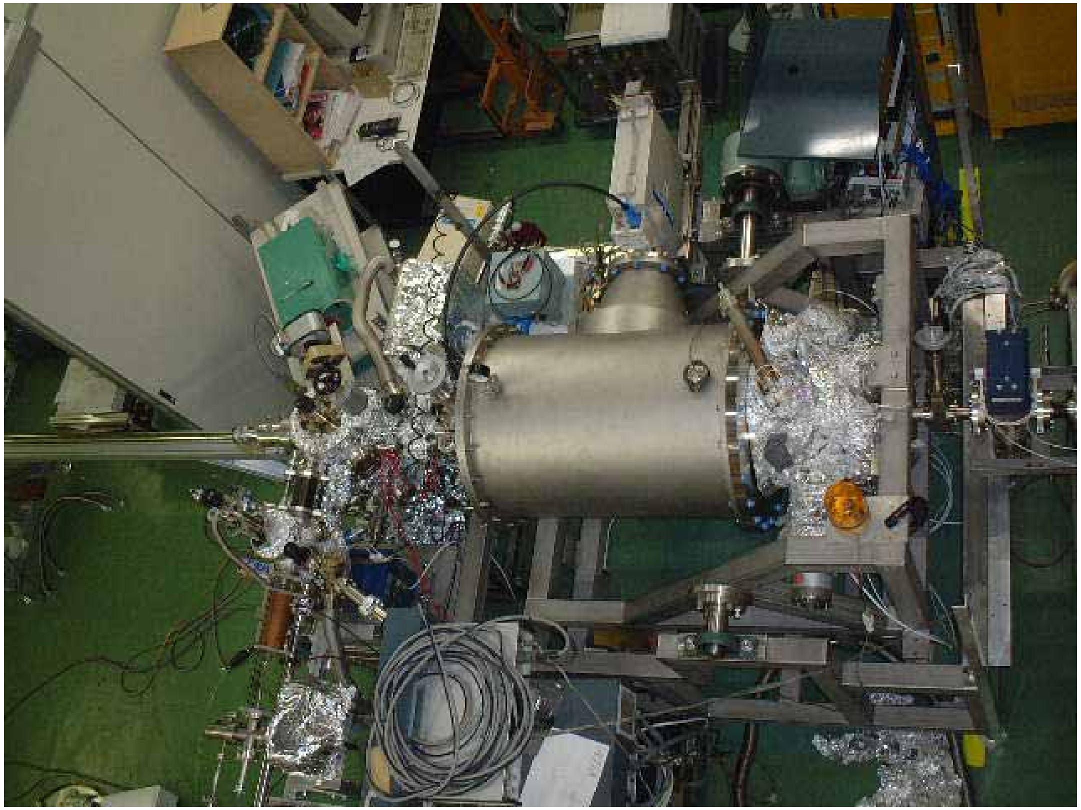
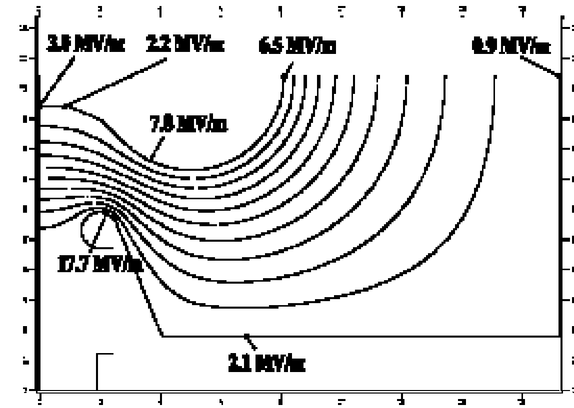


- Separating e⁻ gun and NEA activation chamber using Load-lock system
- Ceramic insulator are divided into some segments for separating high voltage

200kV can be supplied

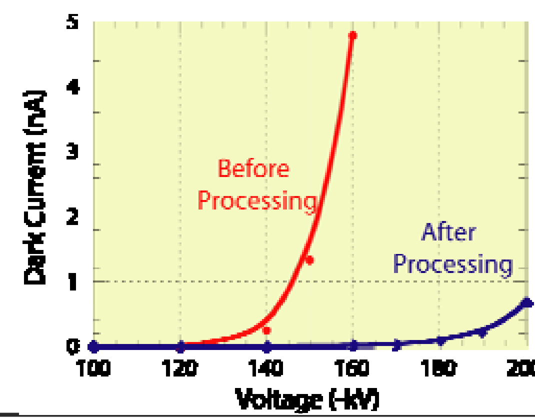
Electrodes



POISSON simulation

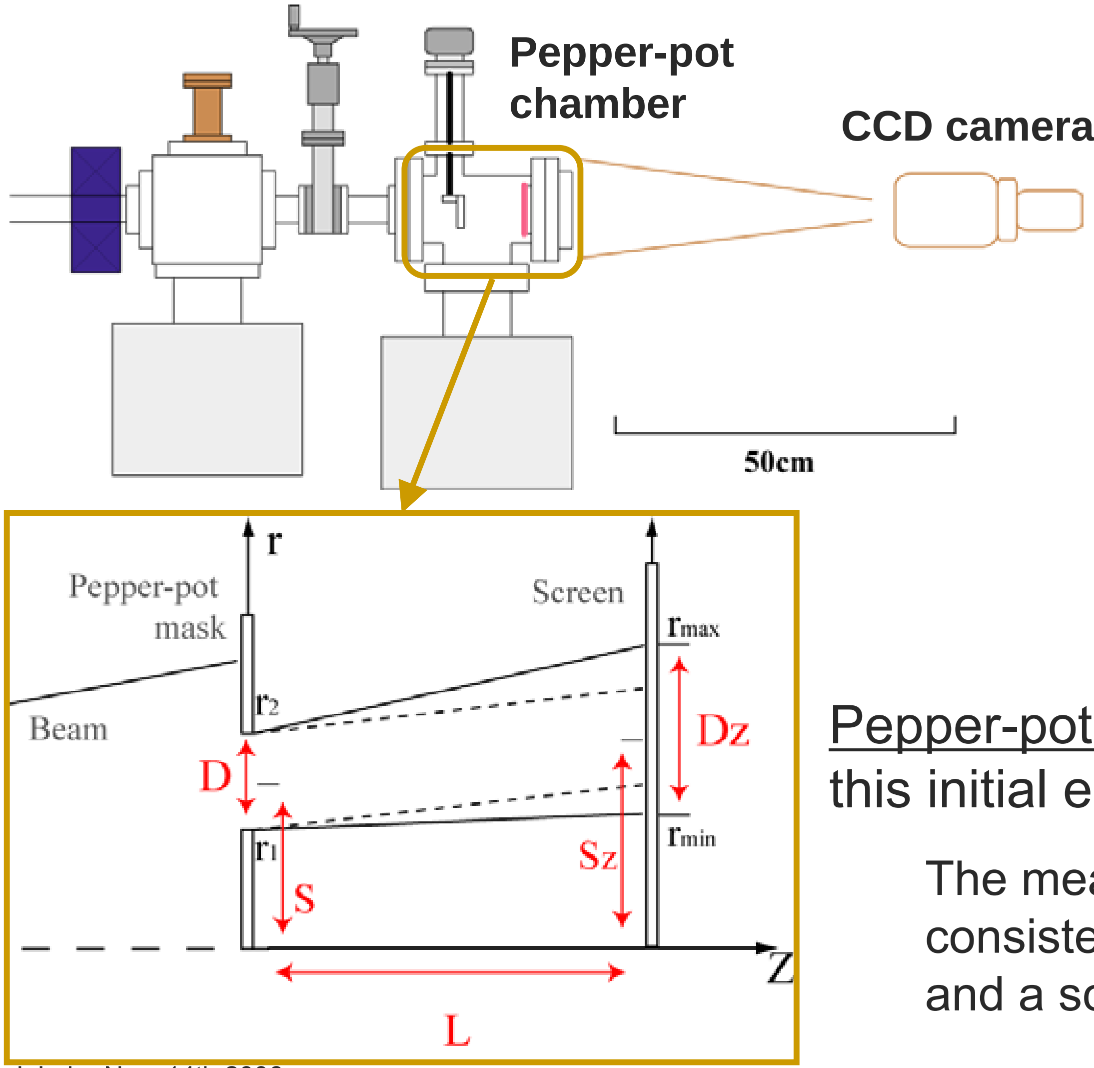
Maximum Field Gradient at 200kV	
Photocathode	3.0MV/m
Cathode electrode	7.8MV/m

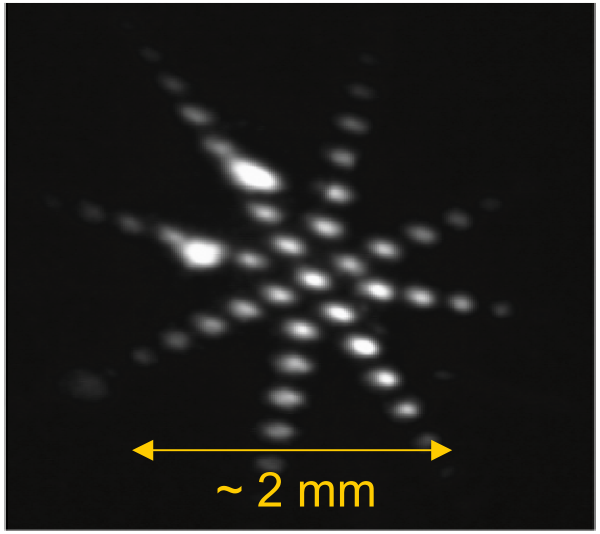
High voltage test



Measurement Setup

- Emittance Measurement System





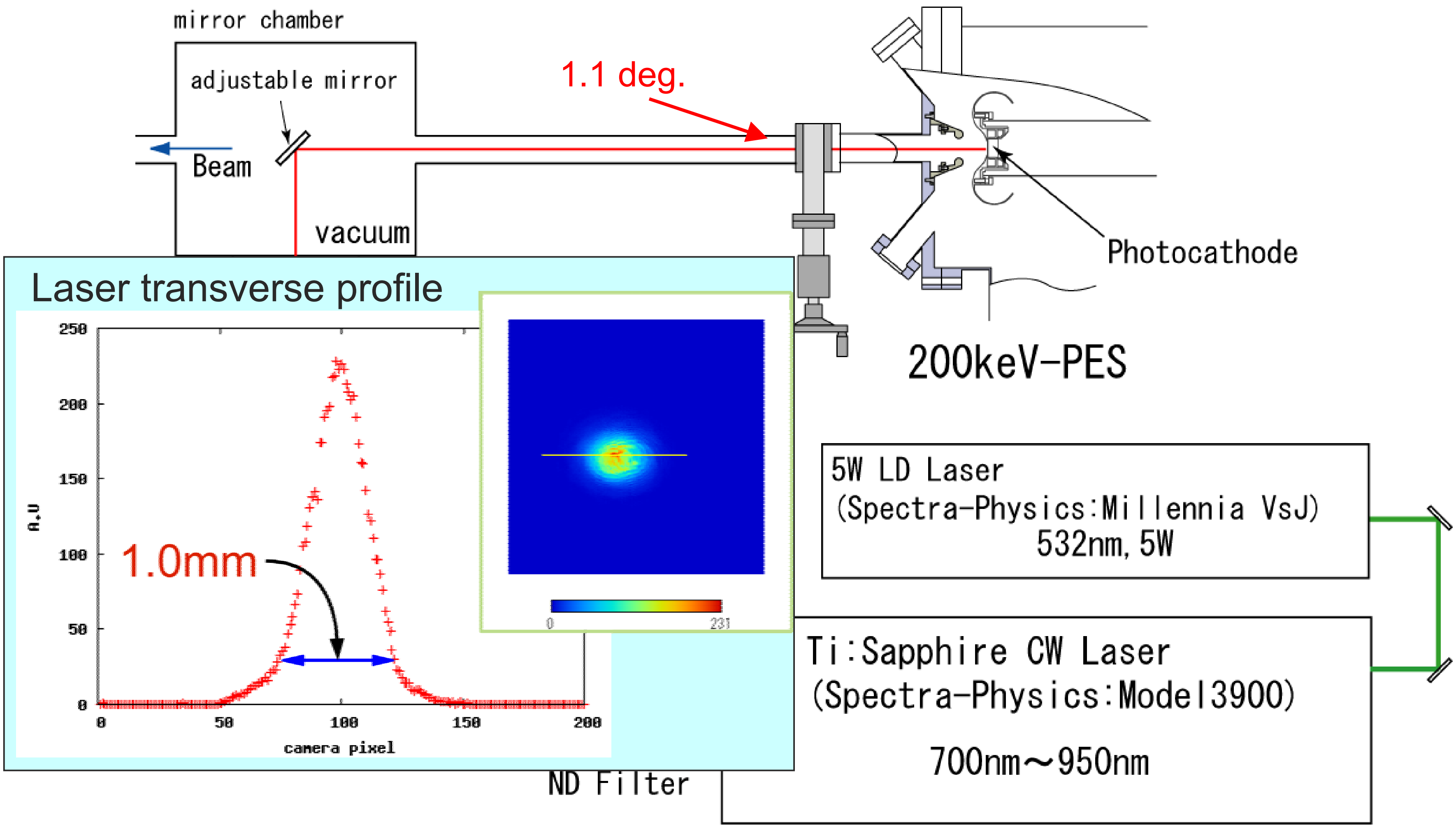
CCD image
(30 shot integration)

Pepper-pot method was adopted for this initial emittance measurement.

The measurement system was consisted of a pepper-pot mask and a scintillation screen.

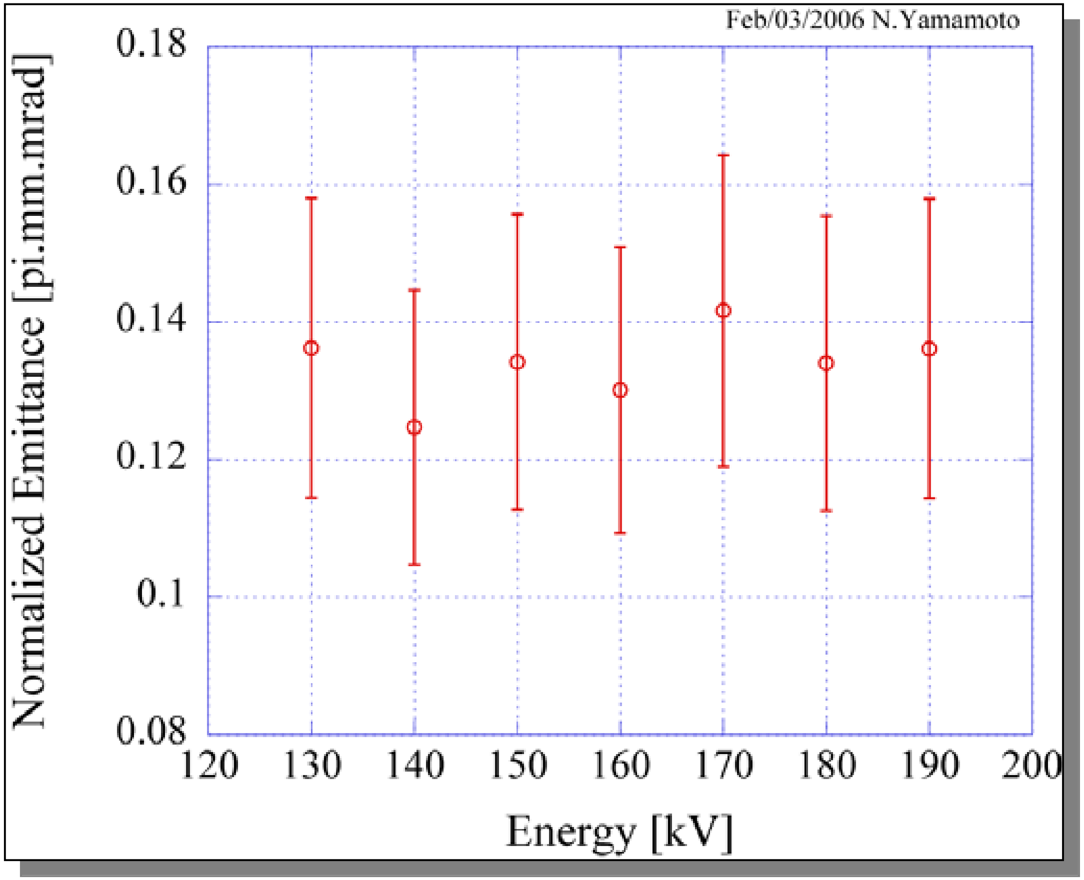
Measurement Setup

- Laser system



Emittance Measurement Results

- Beam energy dependence



Sample : GaAs-GaAsP strained superlattice

Wavelength : 759 nm

Laser size : ϕ1mm

Current : 10~15 nA

Y-normalized rms emittance

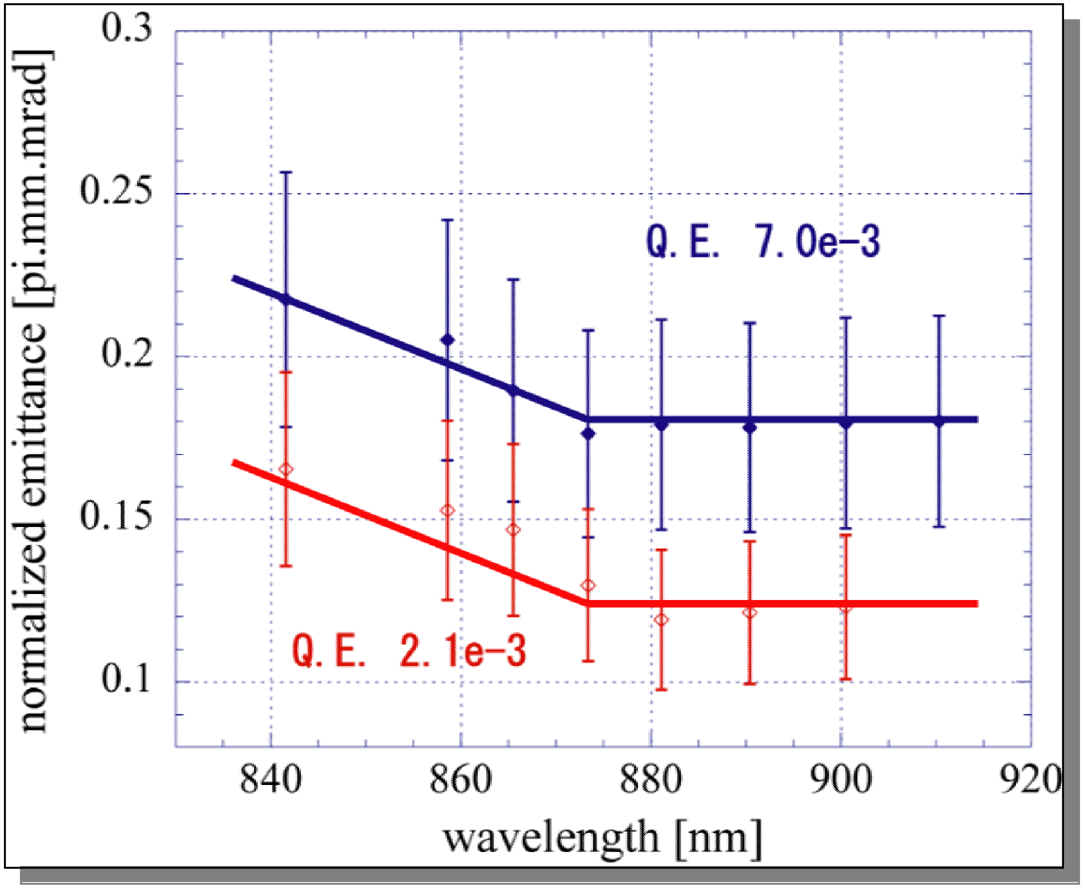
Independent of beam energy

↓

Space charge effect was negligible in this measurements

Emittance Measurement Results

- Photon energy dependence (Bulk-GaAs)



$$\varepsilon = \frac{R}{2}\sqrt{\frac{2E}{3m_e c^2} + \frac{k_B T}{m_e c^2}}$$

E: electron extra energy
R: beam spot size

QE = 7.0 e-3

Average in constant region:

ε =0.18±0.03 πmm.mrad

$k_B T$ -> 66 meV (fit)

QE = 2.1 e-3

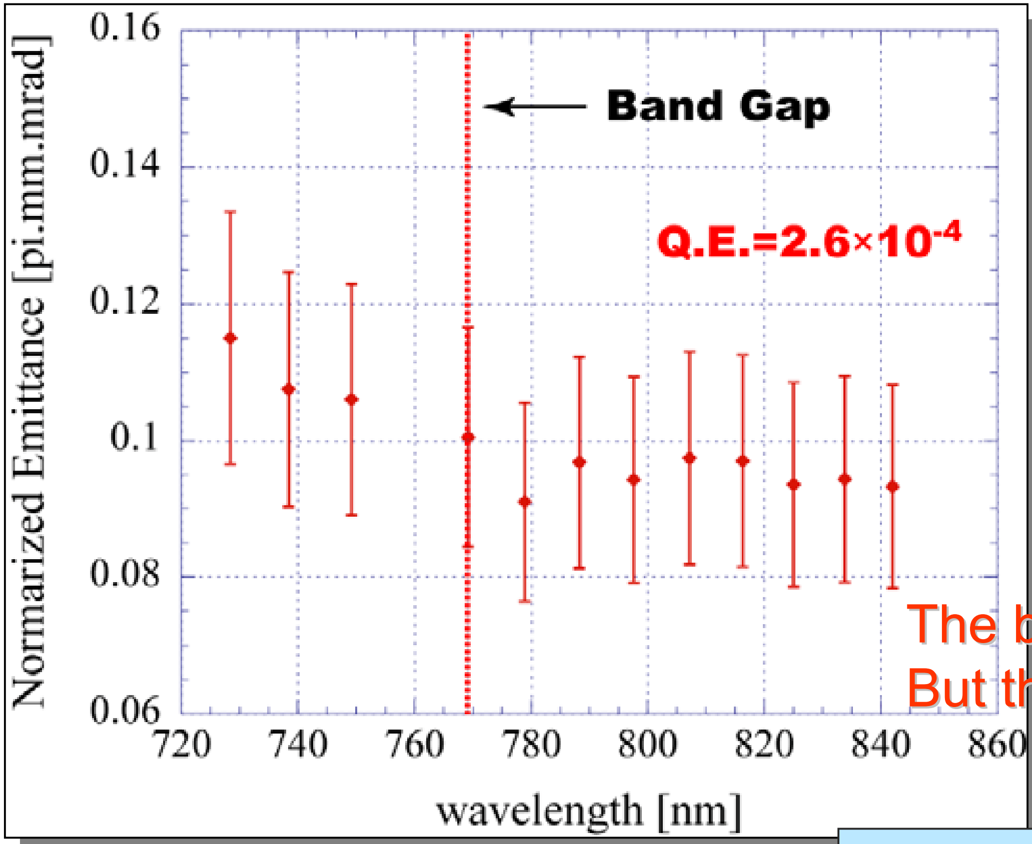
Average in constant region:

ε =0.12±0.02 πmm.mrad

$k_B T$ -> 29 meV (fit)

Emittance Measurement Results

- Photon energy dependence (GaAs-GaAsP)



Sample : GaAs-GaAsP strained superlattice

Beam energy : 120 keV

Laser size : ϕ1mm

Current : 10~15 nA

y-normalized rms emittance

The behavior is similar to bulk-GaAs.
But the value is smaller.

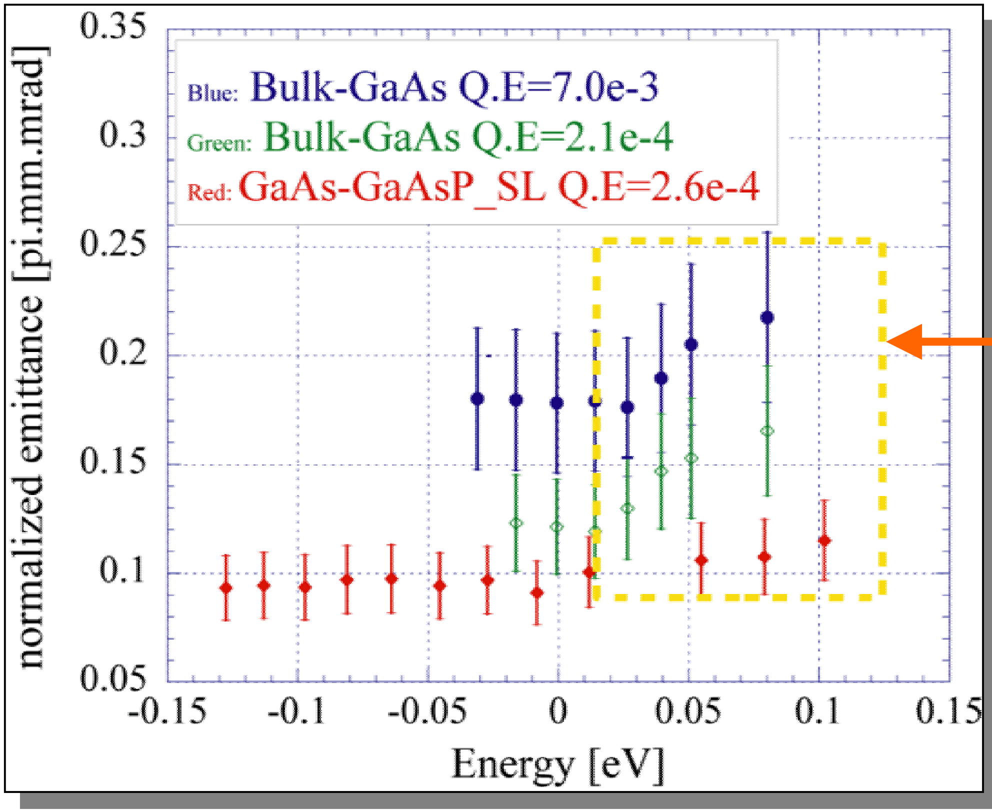
Average in constant region :

$\varepsilon = 0.096 \pm 0.015$ πmm.mrad

Emittance Measurement Results

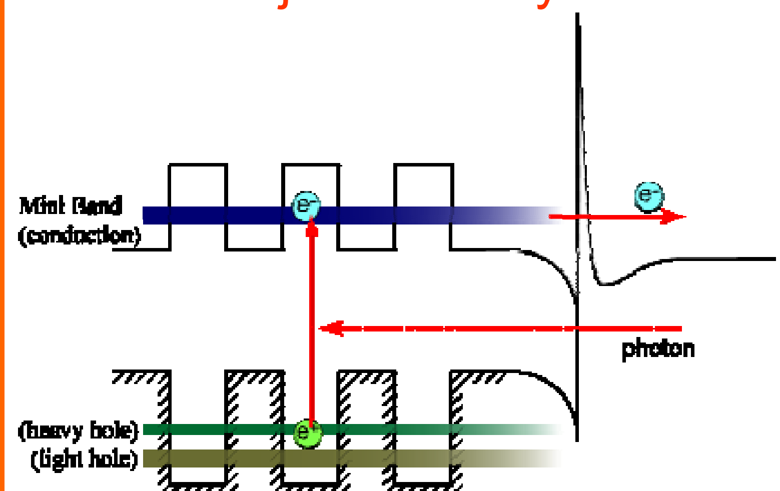
- Photon energy dependence

(by comparison with Bulk-GaAs)



At superlattice photocathode, the increase of emittance is lower than bulk-GaAs

This effect is explained by the width of a joint density of state



Summary of Emittance Measurement

- The emittance of 0.1 πmm.mrad is available using NEA type photocathode
  - To suppress space charge effect
    -> laser optimize, high gradient field gun, …..
- The superlattice structure has an advantage of low initial emittance
  - Emittance increase by electron's extra energy is lower than Bulk-GaAs.

Summary of 2 topics

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- ***Photocathode R&D***
  - GaAs tip as a new type photocathode could extract polarized electron without depolarization effect.
  - Fundamental characteristics were clarified, including the difference of polarization between NEA and F.E.

- ***Emittance measurement***
  - We demonstrated the initial emittance of NEA photocathode had very low value of 1 πmm.mrad.
  - The superlattice photocathode had smaller initial emittance than bulk semiconductor, as expected.