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Summary Report of the Workshop on Polarized Electron Sources and Polarimeters

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A two day satellite-workshop on polarized electron sources and electron polarimeters was held at Department of Physics in Nagoya University just prior to the 1992 Spin Physics Symposium. It was the fourth in a row of similar workshops at Stanford in 1983 [1], at Minneapolis in 1988 [2], organized by C. K. Sinclair and at Bonn in 1990 [3] by E. Reichert. Totally more than 80 people from 35 institutions attended the workshop; about 30 people from U.S.A., Western Europe and Russia and about 50 people from Japan.

The contributions to the workshop were classified into four sessions : 1. Photocathode studies and developments (9 reports), 2. Polarized electron gun for high energy accelerators (10 reports), 3. Low energy electron spin polarimeters (6 reports) and 4. High energy electron spin polarimeters (9 reports). As well known, polarized electrons see their large applications in research fields not only in high energy physics but also in atomic, surface and solid state physics. It is the good transition of this workshop to invite physicists in different fields working with polarized electrons. This time, about 1/3 of attendances came from fields of atomic, surface and solid state physics and they especially contributed to the sessions of 1. and 3.

In the following, I try to pick up the essence of each report and to make some comments from my view point, since speakers wrote their contribution papers after the workshop and they are also published in this proceedings.

1. Photocathode studies and developments

Recently polarized electron beam is considered an important tool especially in particle physics and has been prepared in many accelerator laboratories. For examples, SLC just runs at Z_0 pole energy with polarized beam. SLAC, Mainz, CEBAF, Bonn and others have plans to measure the structure functions of proton and neutron, the electric form-factor of neutron, the DHG sum-rule and so on by using the polarized electrons. It is also expected that polarized e^- beam makes an essential role in the future e^+e^- linear collider experiments. In answer to such urgent needs, the polarized electron source (PES) technology has also been developed intensively [4] and it promises the dramatic improvements over earlier source performances as reported in the workshop.

1.1. Semiconductor photoemission sources

Historically, various types of gas ionization PES were developed. however, at present only the semiconductor (GaAs) type PES has been used for real physics experiments.

Invited talk presented at the 10th International Symposium on High Energy Spin Physics, Nagoya, September 9 - 14, 1992.

Although the principle of GaAs-PES was described in many places [5], a brief review is given here to provide a basis of understandings for physics and technology behind the recent improvements of the source performances.

The GaAs-PES is based on a combination of two fundamental technologies ; laser optical pumping and negative electron affinity (NEA) surface of semiconductor as shown in fig.1.

The former is responsible to the electron spin polarization (ESP) mechanism that the conduction band electrons excited from Γ point (the top of the valence band) are polarized due to the selection rule for the circular polarized photon absorption. The maximum degree of ESP is determined by the properties of the fine splitting of the band structure. For GaAs, it is 50% due to the degeneracy between heavy-hole(hh) and light-hole(lh) bands at Γ point as shown in fig.2. Recent breakthrough against this 50% limitation was reported in this workshop and is explained in subsection 1.2.

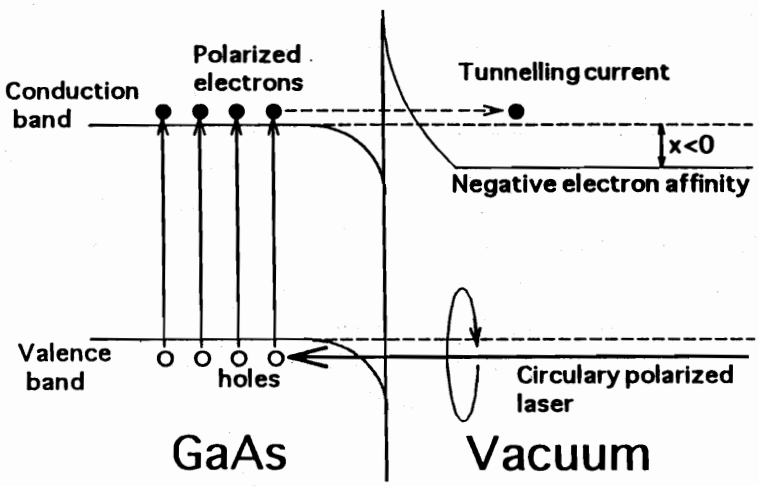

Fig. 1 : Principle of GaAs polarized electron source.

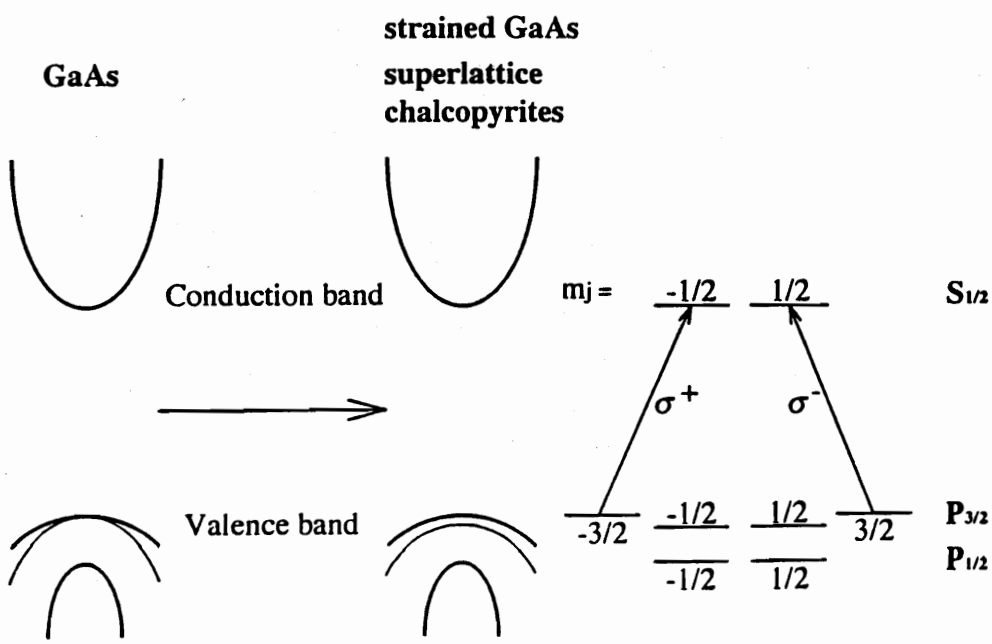

Fig. 2 : Band structures of GaAs and new material photocathodes.

The NEA technique is responsible to the electron emission from conduction band to vacuum. The treatment of heavily p-doped GaAs surface by monolayer coverage of alkali metal and oxidant ($Cs + O_2$ or $Cs + NF_3$ usually used) make it possible to lower the working function to the point where electrons can diffuse into vacuum freely as shown in fig.1. The NEA surface has a great advantage to extract the high current from the cathode with an excellent quantum efficiency (QE) of (1$\sim$ 10)%.

On the other hand, it also brings non-trivial difficulties for the source operation, especially at high energy accelerator. For achieving and maintaining the good QE, the NEA surface must be free of adsorbed residual gases (CO, CO_2 and others) at the sub-monolayer level, which requires the very careful treatment of the photocathode in the ultra high vacuum of ($10^{-10} \sim 10^{-11}$)*torr* range. Obviously the lifetime of photocathode is also governed by the NEA state, which mainly depends on the vacuum condition of each apparatus. It ranges from a few hours to a few hundred hours before *in situ* re-cesiation and/or re-cleaning [4].

1.2. High polarization photocathode

As stated in the introduction, the theoretically - attainable ESP by normal GaAs photocathode is limited below 50%. For overcoming this limitation, the degeneracy at Γ point must be removed as shown in fig. 2, replacing the normal GaAs by new semiconductors. For the last decade, three candidates : ternary chalcopyrites, AlGaAs-GaAs superlattice and strained GaAs have been examined and the breakthrough came at last in 1991 supported by the recent crystal-growth technology. Polarizations of 71% by AlGaAs-GaAs superlattice [6], 71% by strained InGaAs [7] and 86% by strained GaAs [8] were observed at Nagoya-KEK, at SLAC and at Nagoya, respectively.

At present, the strained GaAs photocathode is considered most promising due to its higher ESP than others. The strained GaAs photocathode was made by growing a thin GaAs epilayer on a thick GaP_xAs_{1-x} buffer substrate by a MOCVD apparatus. Since the lattice constant of GaP_xAs_{1-x} is smaller than that of GaAs, biaxial in-plane compression is induced in the GaAs layer and it results in tensile strain along growth direction. Typical behavior of ESP and QE as a function of laser wavelength are shown in fig. 3, which was firstly observed by Nagoya group.

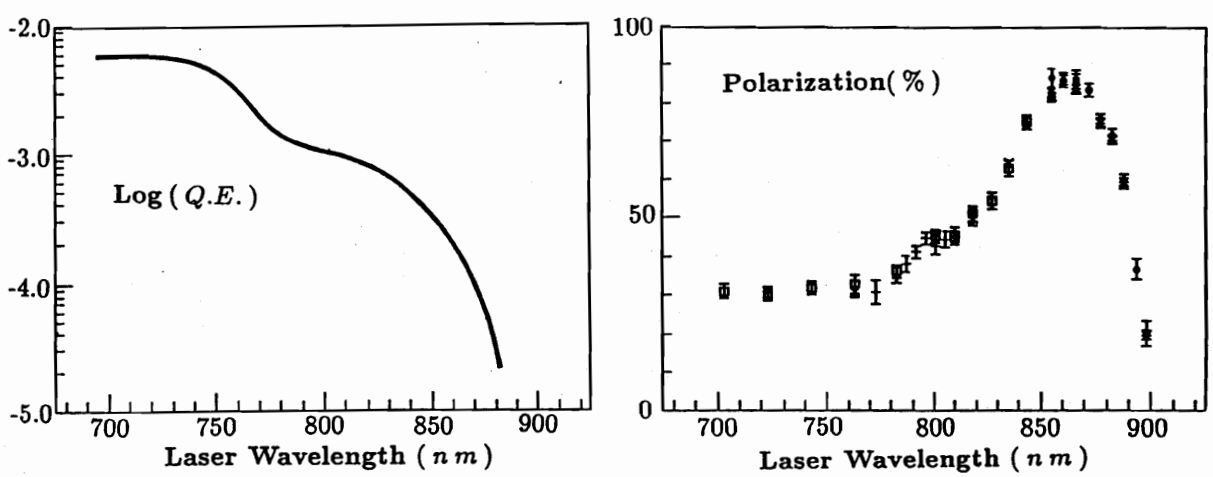

Fig. 3 : Quantum efficiency and polarization of photoelectrons from strained GaAs as a function of laser wavelength.[8]

For understanding detailed properties of strained GaAs layer, the following experimental data seem to be indispensable, (I) The correlation among residual strain, lattice-mismatch and GaAs epilayer thickness and (II) The dependence of ESP on residual strain in GaAs epilayer.

H. Aoyagi (Nagoya), T. Saka (Daido Steel Co.) and T. Maruyama (SLAC) reported on results obtained from various strained GaAs layers with different combinations of thickness(t) and phosphorus fraction (x) in GaAsP substrate.

Concerning (I), a two dimensional plot of $\varepsilon_R / \varepsilon$ and t/t_c using the data of Nagoya and SLAC samples is made as shown in fig. 4, where ε_R, ε and t_c denote the residual strain, the amounts of lattice-mismatch and the Matthews critical thickness for coherent growth, respectively. In spite that each sample has a different combination of (x, t), there seems to be a clear correlation between $\varepsilon_R / \varepsilon$ and t/t_c. It was also demonstrated that the release of strain occurs partially in the epilayer and more than $\sim$ 50% strain remains up to the thickness of a few tens of t_c. This fact is the most important feature for feasibility of strained GaAs photocathode, because it assures both requirements of large lattice-mismatch for high ESP and proper (not so small) thickness for reasonable QE. The QE more than 0.1% was already achieved with ESP higher than 80% at SLAC and at Nagoya.

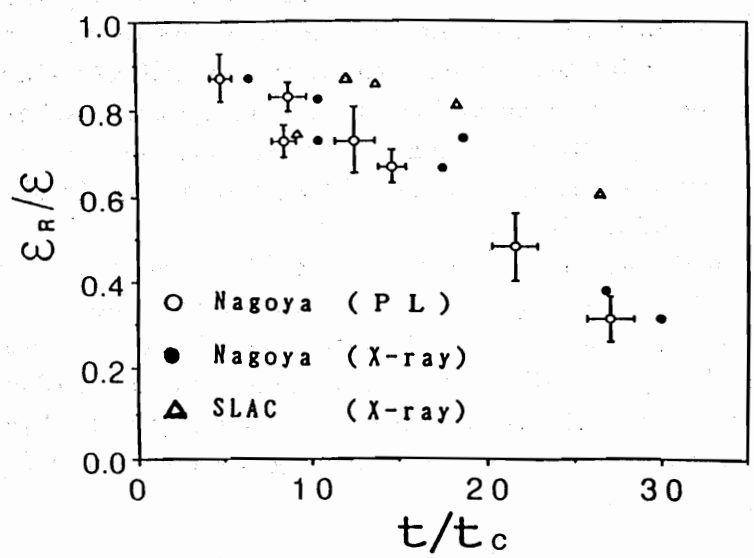

Fig. 4: Relaxation of strain in GaAs layer. [9] [10]

Concerning (II), the maximum ESP attained by Nagoya samples was plotted in fig. 5, as a function of their residual strain. It shows that the ESP has a clear dependence on the strain, especially for the region of smaller band splitting than 30 meV. For region of larger band splitting, ESP seems to be saturated at the level of $\sim$ 90%. T. Uenoyama (Matsushita Elec. Co.) tried to explain this behavior by his theoretical model which takes into account of band mixing between hh and lh states and finite temperature effects. His model seems to explain qualitatively the gross structure of strain dependence of ESP.

H. Horinaka (Osaka Pref.) reported on a preliminary result of measurement of circular polarization photoluminesence from strained GaAs.

The strained InGaAsP layer grown on GaAs substrate has been examined by Novosibirsk group [11]. They could obtain the good QE and good life time performances, although the result of ESP measurement is not yet reported.

Y. Kurihara (KEK) reported on results of cathode of GaAs-AlGaAs superlattice (SL) in which the degeneracy at Γ point is also removed by the quantum size effect. The maximum ESP of ~ 70% with QE of 0.01% was attained at the laser wavelength of ~ $775nm$ by the first successful sample which consists of 20 wells with total thickness of $0.1\mu m$ and p-doping density of $\sim 5 \times 10^{18}/cm^3$. Recently more interesting data was obtained by a sample with lower p-doping density of $\sim 5 \times 10^{17}/cm^3$, which gave the maximum ESP of 71%, but much better QE of ~ 0.2% at the laser wavelength of ~ $750nm$.

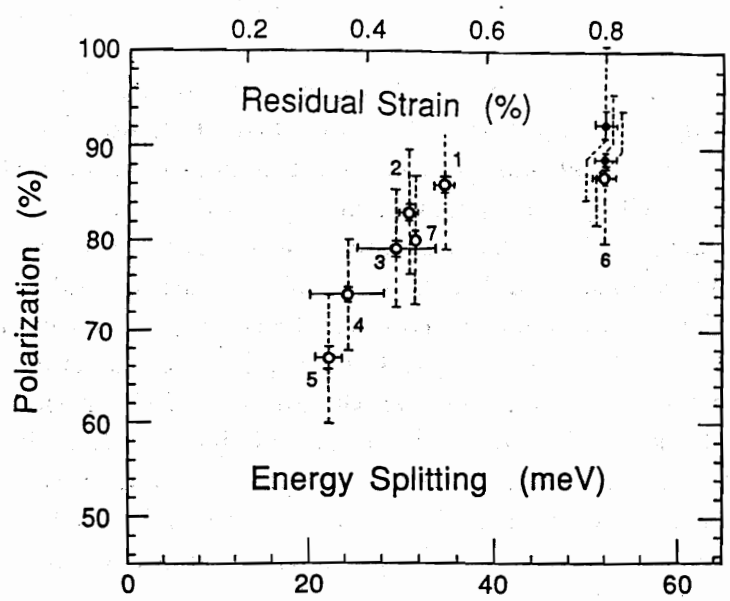

Fig. 5 : Strain dependence of maximum polarization.[9]

The QE limitation comes mainly from the fact that only the single excitation from hh (or lh) band is allowed for high polarization photocathodes. For strained GaAs, in addition, the electrons are excited from the state of low density near the band edge, which shows the $\sqrt{E}$ behavior. On this aspect, the SL structure has an advantage compared with strained GaAs, because it brings the constant state density with energy of valence band electrons. Another idea was proposed by Novosibirsk group for further improvement of QE by using the graded-index SL structure. [11] There seems to be still enough space to improve the QE for strained GaAs and SL photocathodes by new ideas or devises.

In table 1, the typical values of ESP and QE available at present technology by four kinds of photocathodes are summarized.

Cathode	ESP (%)	QE (%)	Ref.
Bulk GaAs	~ 30	3 ~ 10	[1]
Thin GaAs	~ 47	~ 2	[13]
Strained GaAs	~ 80	~ 0.1	[9],[10]
Superlattice	~ 70	~ 0.2	[12]

Table 1 : Performances of four kinds of photocathodes

For evaluation of advantages of new cathode, we must consider about the figure of merits of the sources by P^2I/I_0, where P equals to ESP, I and I_0 denote the available intensity and the maximum intensity accepted by an injection linac or by experimental conditions, respectively.

1.3. Improvements of quantum efficiency and life-time

Apart from the high polarization performance, QE and life-time performances are also essentially important for PES. There were interesting reports from SLAC and Mainz on this subject.

D. Schultz reported that ~ 1.5 times higher quantum efficiency was obtained by cooling the GaAs photocathode to $\sim 150\,K$ than that at $300K$. It is noted this performance was achieved by the SLC gun which has very good ultra-high-vacuum with total pressure of $\sim 1 \times 10^{-11} torr$ and the CO partial pressure of $\sim 2 \times 10^{-12} torr$.

On the study of fatigue of the NEA surface, the interesting work was reported by E. Reichert (Mainz). They measured the amount of Cs, carbon and oxygen on the NEA GaAsP surface by XPS (X-ray photoelectron spectroscopy). As an example, the amounts of Cs and extracted photocurrent are plotted as a function of time in fig. 6. It seems that there is no intimate correlation between the amount of Cs on the surface and that of photocurrent. They took another data which showed that Cs sticks firmly to the GaAsP surface. As a conclusion, they insist that GaAsP photocathode fatigue is not due to the loss of Cs from the surface. Carbon and oxygen are also excluded by their data from the elements which may cause the fatigue of NEA surface. They are now trying to improve the sensitivity of apparatus for searching other impurity elements.

T. Mizoguchi (Gakushuin) reported also on the results of Auger electron study of GaAs surface in relation to both of thermal and chemical treatment.

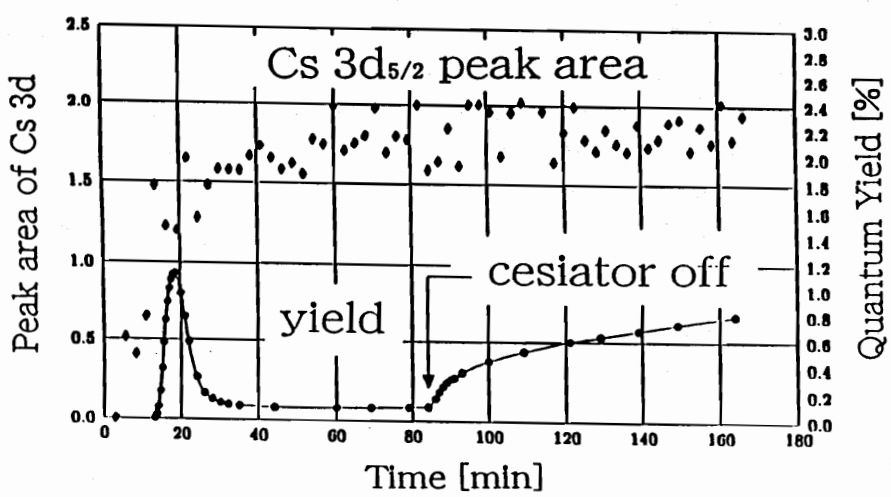

Fig. 6 : Amounts of Cs on NEA surface and quantum efficiency as a function of time.

2. Operational Polarized Electron Source for HE Accelerator

As for applications of polarized e^- beam, there were considered three different cases which depend on the accelerator and experiments, such as, (1) low or medium intensity CW (or pulsed) beam with polarized target, (2) intense CW (or pulsed) beams for high Q^2 or parity violation experiments and (3) high peak current beams for linear colliders.

D. Schultz (SLAC) reported on the first successful PES operation at SLC, which was one of the highlight reports in the workshop. The bulk-GaAs gun has produced 120 keV polarized electrons with intensity of $\sim 6 \times 10^{10} e^-$ ($5\,A$ peak current) in a $2ns$ bunch. It is the same intensity as normal e^- beam. At the early test stage, the gun suffered from the so called high-voltage break down phenomenon, but now the spark current was suppressed to the level of $\sim 20\,nA$ at 120 KV. Other typical performances are following; the initial QE of ($5\sim 10$)%, lifetime of a few days and the average ESP (at source) of 22%, where the cathode temperature has been kept at $\sim 0°C$. The typical history of QE during the run is shown in fig. 8, where A indicates re-cleaning and activation, while C indicates only re-cesiation.

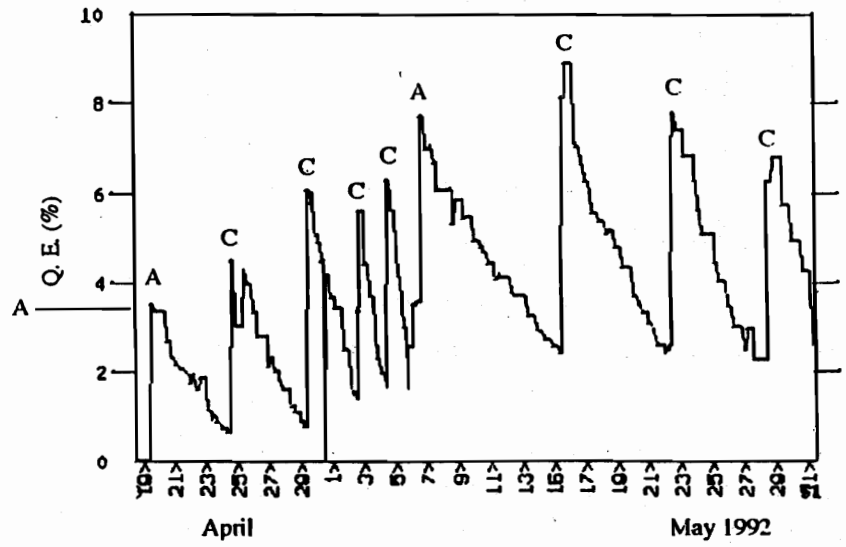

Fig. 7 : Typical history of quantum efficiency during SLC run.

Such performances of SLC gun seems to be sufficient, except the low ESP due to the use of bulk GaAs cathode. As a next step, it is urgently required to replace it by a new cathodes with much higher ESP. [14] M. Woods (SLAC) reported that a Ti:Sapphire laser pumped by a frequency doubled Nd:YAG laser has been developed for this purpose. It is designed to produce $\sim 400\mu J/3.5ns$ pulse at $120\,Hz$ in the wavelength range of $(750-900)nm$. Other systems of Ti:Sapphire lasers pumped by a flushlamp or a Argon CW laser have been also developed at SLAC for the fixed polarized target experiments.

J. Clendenin (SLAC) introduced plans for SLC gun improvements. They contain interesting devises such as a load lock cathode transfer system and an inverted gun geometry which can eliminate field emission from the cathode support tube to high voltage ceramic.

K. Itoga (KEK) reported on the status of construction of proto-type sources for a future linear collider in Japan (JLC) at KEK and at Nagoya.

M. Woods (SLAC) reported another interesting phenomenon called "charge limitation" which was observed during the test run of SLC gun in 1991. The data show that the maximum charge extracted from a bulk GaAs cathode near band gap threshold in a short pulse was less than the space charge limit. [15] This behavior of saturation is significant for the cathode with low QE and the charge limit seems to be proportional to QE, as shown in fig. 8.

Although the reason is not yet fully understood, SLAC people try to explain such a behavior using the concept of the solid state plasma produced inside GaAs. The key feature seems to be the bad NEA surface which causes the increase of plasma density in

solid, resulting in the "charge limitation", as the plasma state prevents the conduction electrons to escape into vacuum.

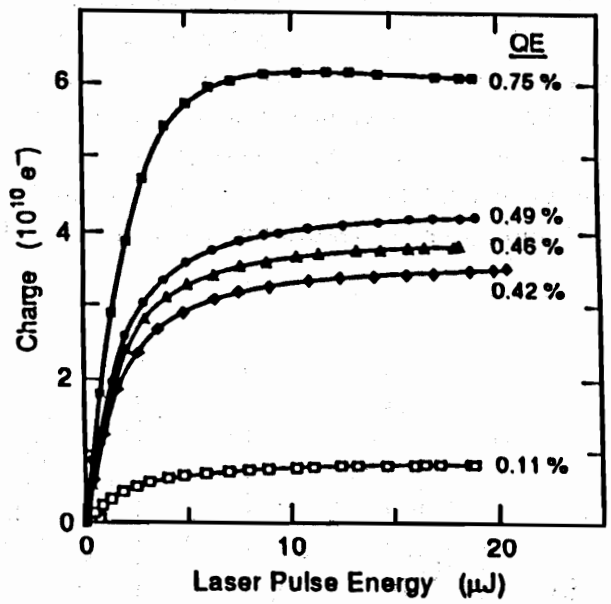

Fig. 8: Extracted total charge versus laser power for different NEA states.

In my personal guess, this phenomenon is also expected to occur for strained GaAs cathode in case of the bad NEA surface, but the "charge limit" may be as same as for bulk GaAs in spite of its intrinsic low QE. For applications of new high polarization cathodes to accelerators, there seems no fatal limitations at present, although both of laser power limitation to avoid "laser burning" and "charge limitation" must be checked by further experiments, hopefully in very near future. [16]

K.H. Steffens (Mainz) reported that polarized DC electron beam from GaAsP was already accelerated by 855 MeV MAMI and $\sim 4\mu A$ beam with ESP of $\sim$ 33% was supplied to the first physics experiment. The direction of spin vector at target point was well adjusted by a Z-spin manipulator in the 100 KeV injection beam line and it turned out that depolarization effect during acceleration was smaller than a few %. Many physics experiments are scheduled using the polarized beam in near future.

S. Voigt (Bonn) reported on the PES for 3.5 GeV ELSA. They could produce the pulsed beam of $25\,mA/(1\mu sec$ bunch) by irradiating a bulk GaAs cathode with laser power of $2.5mJ$/pulse supplied by a flushlamp pumped Ti:sapphire laser with a wavelength of $730\,nm$. The construction of a new PES for a 50 KeV injection linac is also advanced and its status was reported by D. Wehrmeister (Bonn).

PES developed at several intermediate energy accelerators, such as Illinois/CEBAF, Orsay, Kharkov, Novosibirsk will also come into operation within a few years and many physics results will be produced in 1990's.

3. Low Energy Electron Spin Polarimeters

For characterizing the performance of a polarimeter,it is convenient to use the figure of merit(FM) defined as $FM = S^2 I/I_0$, where S is a analyzing power and $I(I_0)$ is the scattered(incident) beam intensity.

The Mott polarimeter is based on spin-orbit force and still a standard device for determining the polarization of electron beam with energies from a few eV up to a few MeV. It is also used as a device for calibrating the other types polarimeters at various laboratories.

J. Fujii (Tsukuba) reported on a 100 KeV Mott detector designed for a spin-resolved photoelectron spectrometer with a revolver undulator at the Photon Factory of KEK. They calibrated this device with a GaAs source and its FM was estimated as 1.5×10^{-5}.(After the workshop, it was improved to be 1×10^{-4}.)

The LEED spin polarimeter is based on spin-orbit interaction and uses a low energy electron diffraction scattering from a tungsten W(001) single crystal.

C.M. Schneider (M.P.I., Halle/Saale) reported on this type of polarimeter which has FM of $\sim 2 \times 10^{-4}$ at 104.5 eV.

E. Kisker (Düsseldorf) reported on another type of polarimeter based on exchange force, which uses the very low energy electron diffraction scattering from the magnetized film of Fe(001). This polarimeter has an advantage in higher FM by an order of magnitude compared with others and $FM \sim 2 \times 10^{-3}$ had been achieved at 12 eV. The above three polarimeters were already employed for the experiments combined with circular polarized photons produced by synchrotrons.

T. Furukawa (Hitachi) reported also on the polarimeter based on the exchange force, which measures the current absorbed by a target of Fe(110). To eliminate the noises, a lock-in detection method was newly employed, preparing two Fe(110) targets with magnetizations parallel but opposite to each other. The test and improvement of apparatus is advanced to obtain the final FM of $\sim 10^{-3}$.

The absorption current method is based on spin-orbit force and uses the polarization dependence of absorbed current by the target. T. Suzuki (Sophia) reported his results of measurement on the polarization dependence of the zero-crossing energy point where the absorption current becomes zero, examining Al, Cu, Mo, Ag and Au targets.

The optical method is based on the relation with three angular momenta, that of orbital and spin of incident electron and that of spin of emitted photon from the excited "two electron heavy atom" like Zn, Cd and Hg target. T. Suzuki (Sophia) found experimentally that even if the incident electrons are not polarized, the emitted photons are slightly polarized.

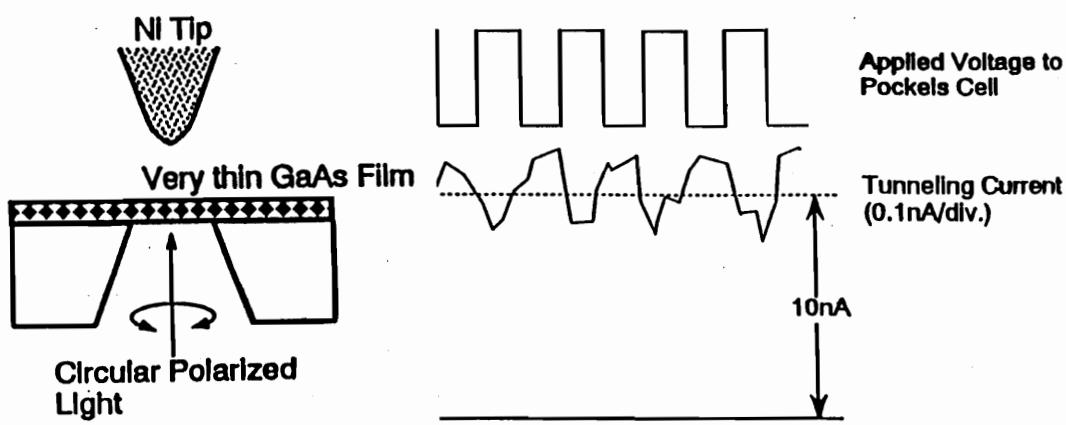

Fig. 9 : Concept (left) and data (right)of experiment for detection of spin polarized tunneling current.

The development of spin polarized STM (scanning tunneling microscope) is considered

as an interesting subject related to polarized electrons. For such a device, it is essential to separate the spin dependent component from the topographic component in tunneling current. This cancellation of topographic information is possible if the spin direction of electrons emitted from a tip can be reversed without any changes of other conditions. This is, however, not so easy and no one succeed in inventing such a tip for spin-STM.

K. Sueoka (Hokkaido) reported on an experiment to demonstrate the existence of spin dependent tunneling current. In their experiment, a combination of Ni tip and GaAs sample was employed, as shown in fig. 9. Although this is the reversed configuration required for the universal use of spin-STM, the photo-induced current was detected which changed with the modulation of circular polarization of exciting laser photon as shown also in fig. 9.

4. High Energy Electron Spin Polarimeters

There has been used three kinds of scattering process to determine the polarization of high energy electrons; Mott, Möller and Compton and all of them were reported in the workshop.

There were four reports on Compton polarimeters. One is employed at a linear collider of SLC and others are employed at three storage rings of LEP, HERA and TRISTAN. Their status were reported by M. Fero (MIT), R. Schmidt (CERN), M. Düren (DESY) and K. Nakajima (KEK), respectively. Among them, LEP polarimeter was already used as an accurate energy meter and contributed for determination of mass and its width of Z_0 boson. [17] SLC polarimeter was also employed as a physical tool to measure the left-right electroweak asymmetry at Z_0 pole. [18] These two successful operations of Compton polarimeters in physics runs seem to be one of the highlights of this workshop.

On contrary to a polarimeter used at storage ring, a polarimeter for a single shot collider can destroy the beam after e^+e^- collision point. The polarimeter is based on Compton scattering of the longitudinally polarized electron beam off circular polarized photons. The Compton scattered electron beam is separated from the unscattered one by the dipole magnets which are also used as an energy analyzer combined with a multi-channel Cerenkov detector. By their system, a statistical precision of $\Delta P/P = \pm 3\%$ was obtained within ~ 3 minutes. The total systematic error($\delta P/P$) was estimated to be 3%, dominated by the error of laser photon polarization at the Compton interaction point. Their final goal is to reduce this value to less than 1% in future SLC runs for precise determination of the weak mixing angle of $sin^2\theta_W$ with the error less than 0.001.

For the other three polarimeters at storage rings, the Compton scattered photons which emerge in a narrow cone in backward direction are detected by position sensitive γ-detectors. [19] The transverse polarization of electrons is determined by measuring the vertical shift of centroid position of the γ-distribution between +1 and -1 of laser photon helicity. This shift is estimated to be $\sim 500\mu m(\sim 300\mu m)$ for LEP(HERA) polarimeter for the electron beam with 100% transverse polarization.

LEP developed the multiphoton technique to avoid the background problem and a statistical precision of $\Delta P = \pm 1\%$ was obtained within 1 minute. To reduce the systematic errors, the effects caused by the jitter of e^- beam, the linear component of the circular light, the limited aperture and non-linearity of γ-detector are studied. As a result, combined with a depolarizer system, the polarimeter could calibrate the LEP beam energy with an accuracy of ~ 1 MeV. [17]

HERA polarimeter employed the single photon technique and could obtain a statistical precision of $\Delta P = \pm 1\%$ within 2 minutes. They observed the polarization build-up time and could achieve more than 56% polarization by optimizing machine parameters. The total systematic error($\delta P/P$) was estimated to be less than 10%. For future physics experiments, the longitudinally polarized electron is required at HERA. [20] E. Gianfelice (DESY) discussed the possible depolarization in presence of the spin rotator.

TRISTAN polarimeter employed also the single photon technique and has been used for the polarization build-up time measurement, the compensation of depolarization by harmonic orbit correction and the beam energy measurement by resonant spin depolarization.

In fig. 10, the nicely measured data of polarization build up by LEP and HERA polaimeters are shown.

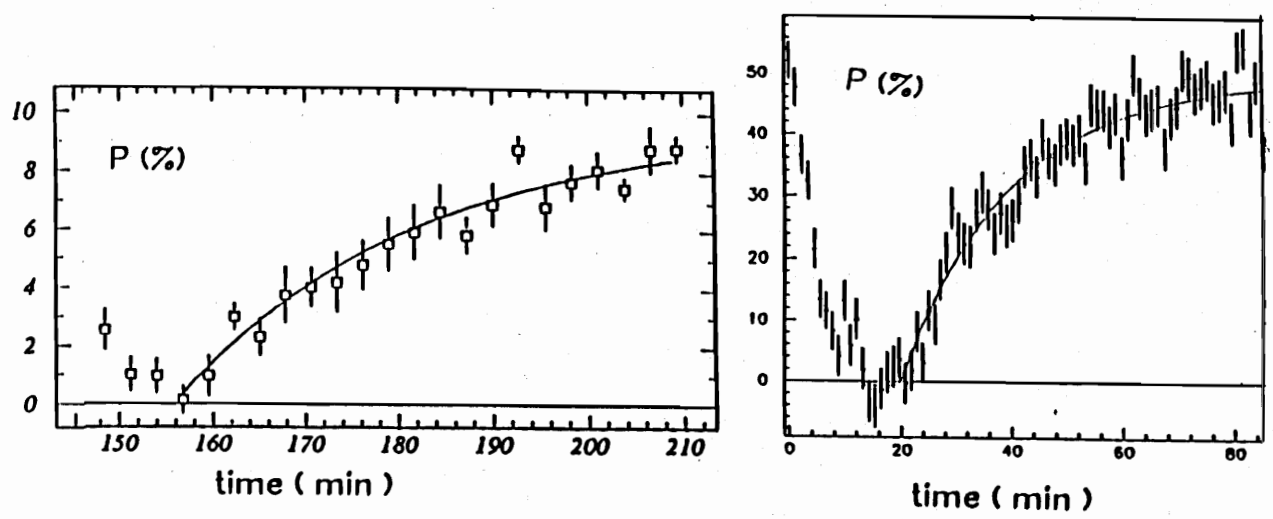

Fig. 10 : Polarizations build up measured by LEP (left) and HERA (right) polarimeters.

There were three reports concerning the Möller polarimeter. Y.M.Shatunov (Novosibirsk) reported a conceptual design of new type polarimeter which uses the $e^{\pm}$ scattering on polarized electrons of the super cold H atoms (0.3K) trapped in the solenoid field(5T) along the storage ring straight section. F. Feinstein (CERN) reported the performances of two kinds of polarimeters which used the μ decay or the μ-electron scattering to measure the polarization of muon beam in the SMC experiment. A comment on a possible source of a systematic error due to the intra-atomic motion of bound electrons made by L.G.Levchuk (Kharkov) was presented by S.B. Nurushev (IHEP).

In conclusion, I think this workshop was held with a very good timing, since there were many remarkable advances in this field during the last two years after the Bonn workshop. I also have a strong impression that many physical results will be produced in forthcoming two years using polarized electrons as important tools in both particle/nuclear and solid state physics.

Finally I would like to thank all speakers, attendances for their excellent contributions and the members of the organizing committee of the workshop, M. Yoshioka (KEK) and A. Kakizaki (ISSP-Tokyo) for their cooperations.

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[10] T. Maruyama *et al.*, Phys. Rev. 46, 4261 (1992)

[11] This work was introduced by Y.M. Shatunov at the workshop and published in this proceedings.

[12] Y. Kurihara *et al.*, Nucl. Instrum. Methods A313 (1992) 393-397

[13] T. Maruyama *et al.*, Appl. Phys. Lett. 55(1989)1686

[14] After the workshop (Feb. 1993), SLC succeeded in accelerating the polarized beam from strained GaAs photocathode with ESP of $\sim 65\%$ (at source) and the intensity of $\sim 6 \times 10^{10}$ e^- / bunch.

[15] M. Woods *et al.*, SLAC-PUB-5894 (1992)

[16] After the workshop, the total charge of $\sim 10 \times 10^{10}$ e^- / bunch was obtained by the SLC test gun at $\lambda = 850\,nm$.

[17] J.P. Koutchouk, "Energy calibration with a polarized beam at LEP" presented at the parallel session of main symposium.

[18] K. Moffeit, "Polarized electron beam at SLAC" presented at the parallel session of main symposium.

[19] D. Barber, "Theory and observation of electron polarization in storage rings" presented at main symposium.

[20] M. Düren, "Electron spin polarization measurements at HERA" presented at the parallel session of main symposium.

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