The self-calibration of a retarding-type Mott spin polarimeter with a large collection angle

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We have developed a compact retarding-type Mott spin polarimeter with a large collection angle at the Hiroshima Synchrotron Radiation Center and obtained a reliable value of the effective Sherman function by a self-calibration method. The spin polarization of secondary electrons was evaluated by extrapolation of the left-right scattering asymmetry at the zero energy-loss limit, which enabled us to obtain the effective Sherman function (S_{eff}) and the figure of merit of our polarimeter at different operating conditions. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2162752]

I. INTRODUCTION

In recent years there has been considerable interest in the properties of nanoscale magnetic materials grown on a semiconducting or metallic surface because of their possible applications in spintronics. Many experimental studies have been performed to understand the peculiar magnetic properties based on the spin-dependent electronic states in the vicinity of the Fermi level. Utilizing the wavelength and polarization tenability of synchrotron radiation, the spin- and angle-resolved photoelectron spectroscopy (SARPES) is a powerful tool to perform such research and this is the motivation to construct a SARPES system at the Hiroshima Synchrotron Radiation Center (HSRC).

The spin polarimeters are usually based on electron scattering by a high Z target. If the electrons are spin polarized, the scattering intensities towards the left and right directions are different due to the spin-orbit interaction. Once we know the left-right scattering asymmetry A denoted as

$$A = \frac{N_L - N_R}{N_L + N_R},$$

which can be obtained by measuring the electron counts at the left (N_L) and right (N_R) detectors, the spin polarization of incident electrons can be obtained by

$$P = A/S_{\mathrm{eff}},$$

where S_{eff} is the effective Sherman function, which differs from the theoretical Sherman function S of free atoms due to the plural and multiple scattering process in the solid target.[1] Since the inverse square of the statistical error of the observed spin polarization is proportional to IS_{eff}^2, $\varepsilon = (I/I_0)S_{\mathrm{eff}}^2$ is usually termed as the figure of merit (FOM) of the Mott spin polarimeter, where I_0 is the number of electrons entering the polarimeter and $I(=N_L+N_R)$ corresponds to the total number of scattered electrons measured by the left and right detectors.

The determination of the S_{eff} of a spin polarimeter is indispensable to a correct evaluation of the electron spin polarization. Although several kinds of determination methods have been proposed, the estimation of S_{eff}, however, is not an easy task. For a conventional Mott spin polarimeter, which is generally operated at several hundreds keV, the determination of S_{eff} by a double scattering of unpolarized electrons is the most straightforward and conceptually the simplest method, but its setup is complicated and the elimination of the instrumental asymmetries is difficult.[2] A similar and more difficult method, which employs a polarized electron beam with an auxiliary target, has the advantage that the S_{eff} can be evaluated without knowing the absolute value of spin polarization of incident electrons.[3] However, further studies show that its accuracy is limited by a systematic depolarization effect resulting from the multiple scattering in the auxiliary target.[4] The absolute calibration can be achieved by the usage of spin-polarized electrons with its well-known polarization from He metastable atoms[5] or the GaAs cathode with a negative electron affinity surface,[6] but the setup of the spin-polarized electron source itself is hard work. Therefore, reliable and simple calibration methods are strongly desired. For a conventional spin polarimeter working at high operating voltages, the polarimeter has been calibrated by the extrapolation of the scattering asymmetry to a zero target thickness, where the magnitude of S_{eff} would approach the theoretical free-atom value. A precision of 0.8% (Ref. 7) has been achieved for a 100 keV conventional spin polarimeter. In principle, for a retarding-type Mott spin polarimeter, the extrapolation of scattering asymmetry to zero energy loss ($\Delta E_{\mathrm{loss}}=0$) is equivalent to that of the zero target thickness[1] and easier to be realized, because only the retarding voltage needs to be varied and no physical movement is required. However, there is actually a serious problem for the evaluation of S_{eff} by the extrapolation process for a retarding-type

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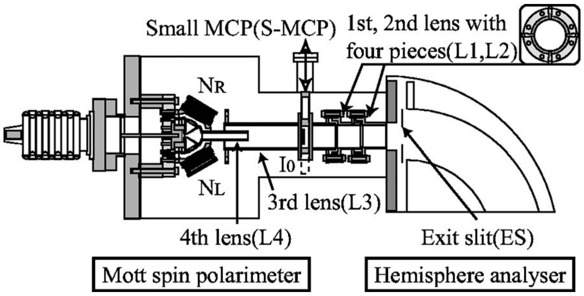

FIG. 1. The schematic figure of the Mott spin polarimeter combined with the transport lens and the hemispherical electron energy analyzer.

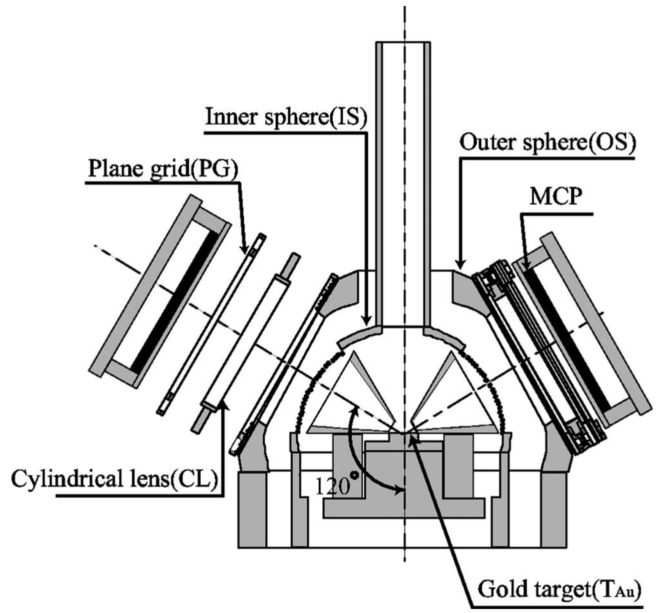

FIG. 2. The structure of the retarding-type Mott spin polarimeter.

polarimeter, because a large difference was observed between the value of S_{eff} at $\Delta E_{\mathrm{loss}}=0$ and the theoretical Sherman function of the free atom. The reason is that the plural scattering cannot be avoided even for zero ΔE_{loss} when the operating energy is under 50 keV.[7–9] So regardless of the fact that the extrapolation to zero inelastic energy loss is considered to be a well-established calibration technique for retarding-potential polarimeters, in practice, no polarimeter, to the best of our knowledge, has been reported to be successfully calibrated by this method.

The highest efficiency of retarding-type polarimeter was achieved by Qiao *et al.*[10] In their design, a special retarding-field electron optics was adopted to achieve a large collection angle for scattered electrons. For this polarimeter, it was reported that the magnitude of asymmetry did not monotonically increase with the decrease of ΔE_{loss} and the reason was attributed to the special character of the retarding electron optics. They concluded that the self-calibration was impossible for this type of spin polarimeter. In this report, we show how the self-calibration can be realized by the careful determination of the experimental condition for $\Delta E_{\mathrm{loss}}=0$.

II. THE STRUCTURE OF OUR SARPES SPECTROMETER

The spectrometer consists of a compact retarding-type Mott spin polarimeter and a hemispherical electron energy analyzer (OMICRON EA-125) as sketched in Fig. 1. The structure of the Mott spin polarimeter is similar to that reported by Qiao *et al.*[10] We have modified only the input lens system that is used to transfer the electron beam from the exit slit of the electron energy analyzer to the spin polarimeter target. In our lens system, a small microchannel plate (S-MCP) can be inserted in or removed out from the third element (L3). A spin-integrated photoelectron spectrum or I_0, the intensity of electrons entering the Mott polarimeter, can be measured with this S-MCP. The first and second lens elements (L1, L2) are divided into four identical pieces, which are used as electron deflectors besides their main lens functions. With this design, the focusing and transfer of electron beam from the analyzer exit slit (ES) to the center of the gold target (T_{Au}) can be guaranteed. The structure of the Mott spin polarimeter is shown in Fig. 2. The same high voltage of several tens of kilovolts as the operation potential is applied to the fourth lens element (L4) of the input lens system, T_{Au}, and inner sphere (IS). The bias voltage at the outer sphere (OS) is set as the Earth's voltage. In the normal operation mode, ΔE_{loss} is controlled by the bias voltage on the front side of MCP while that on the cylindrical lens (CL) and plane grid (PG) is set as 3 kV. The electrons scattered by the target are decelerated by the retarding optics, which consists of OS, CL, PG, and the front side of the MCP detector. The electrons whose kinetic energy is high enough to overcome the retarding electron field are able to enter the MCP detectors. The angle between the center axis of the retarding electron optics and the incident electron beam is set as 120°.

III. THE SELF-CALIBRATION OF THE MOTT SPIN POLARIMETER

The secondary electrons with 2 eV kinetic energy from the magnetized Ni(110) surface excited by a 10 keV electron beam or He I photons ($h\nu=21.22$ eV) was used as the source of spin-polarized electrons for the calibration of our spin polarimeter. Our experiments confirmed that the spin polarization P of secondary electrons is independent of exciting method. To minimize the stray magnetic field, the Ni(110) sample was shaped into a picture frame with each frame oriented along the $\langle 1\bar{1}1\rangle$ direction, which corresponds to the easy magnetization axis. A clean surface was obtained by repeated cycles of 1000 eV Ar^+ sputtering and annealing up to 600 °C. The sample cleanness was carefully checked by Auger electron spectroscopy (AES). All the measurements were done in the condition that the amounts of impurities were less than the detection limit of the AES. The sample was magnetized by a coil wound around one of its frames. In order to eliminate the instrumental asymmetry, we observed the scattering asymmetry (A) of the secondary electrons by two successive measurements with opposite magnetization direction as described by the following formula:

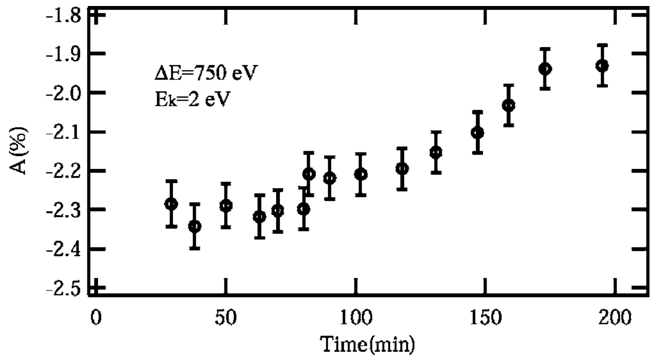

FIG. 3. The observed left-right scattering asymmetry A as a function of time after the cleaning procedure of the Ni(110) sample surface.

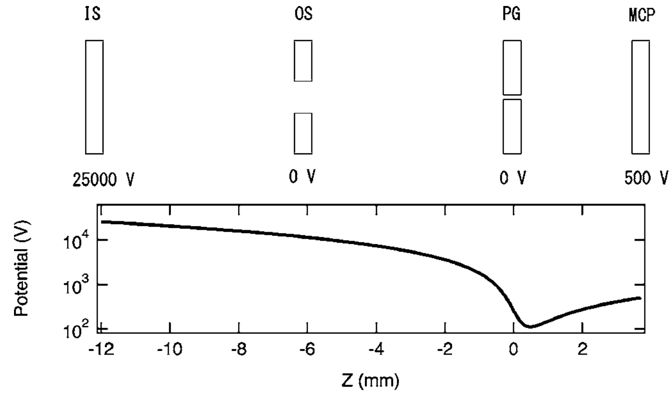

FIG. 4. The simulated potential along the axis of retarding optics.

$$A = \frac{X-1}{X+1}\left(X = \sqrt{\frac{LR'}{RL'}}\right),$$

where L/R and L'/R' are the ratios of count rates of the left and right detectors with opposite sample magnetization, respectively.[1] The incident direction of photons (electrons) was set along the surface normal and the emission angle of secondary electrons was set as 40° from the surface normal. A sample bias of −1 V was applied during the measurements to enhance the emission of secondary electrons.

Spin polarization of photoelectrons is very sensitive to the contaminations on the sample surface. However, the polarization is required to be stable for a long time for a realizable determination of S_{eff}. At the first step, we have studied the duration that the stable polarization could be maintained. The dependence of the scattering asymmetry on the time after the cleaning process has been measured (Fig. 3). The observed asymmetry remained constant for 80 min, then it started to decrease. Therefore, the Ni(110) surface was cleaned every hour during the measurements.

A correct value of the spin polarization P of the secondary electrons needs to be determined before evaluating S_{eff}. If detectors only count electrons that just experienced a single scattering event, the spin polarization of incident electrons can be estimated from the measured scattering asymmetry A_s with the relation $P=A_s/S$, S being the theoretical Sherman function of free target atom. For the retarding-type Mott polarimeters, the retarding field can be used to adjust the ΔE_{loss} of the scattered electrons. Since the probability of multiple scattering is proportional to the traveling distance in the target, and electrons always lose kinetic energy when traveling in the target, the multiple scattering process can be eliminated if ΔE_{loss} is set to zero. In this case, only the electrons with an elastic scattering process, in other words, only the ones travel a very short distance in the target, are permitted to reach the detectors. However, the plural scattering cannot be avoided when the electron energy is lower than 50 keV as in the present case. Therefore, it is impossible to count only the electrons with a single scattering event even if ΔE_{loss} is set to zero. But we can still use the experimental result of the effective Sherman function for zero ΔE_{loss} (S_0) (Ref. 8) to perform relative calibration to determine the polarization of the secondary electrons by the relation $P=A_0/S_0$, where A_0 is the scattering asymmetries at zero ΔE_{loss}.

For retarding-type Mott polarimeters, if the bias on the entrance of detector is set as $+V_{\mathrm{in}}$, only the electrons with energy loss less than eV_{in} electron volts in the scattering process can arrive at the detector. As a result, this bias can be used to adjust the ΔE_{loss} for the scattered electrons. Qiao *et al.*[10] measured the scattering asymmetry as a function of the front bias of MCP (V_{in}). The normal behavior is found when $V_{\mathrm{in}} > 200$ V and that the magnitude of asymmetry increases along with the decrease of V_{in}. However, the abnormal behavior emerged when $V_{\mathrm{in}} < 200$ V and that the magnitude of asymmetry became smaller for lower V_{in}, which caused the failure of extrapolation. They attributed this failure to the special character of the retarding electron optics. After scrutinizing their experiments, we found that the abnormal behavior was most possibly caused by the decrease of quantum efficiency of the MCP when V_{in} was less than 200 V, because the electrons arrived at the MCP with too small a kinetic energy.

In this work, two different bias schemes are used in extrapolation and normal operation modes, respectively. When we perform the extrapolation, the front bias of MCP is kept at 500 V in order to realize the high and constant quantum efficiency and the ΔE_{loss} is adjusted by the applied bias (V_b) at CL and PG assemblage. As a result, the magnitude of scattering asymmetry was found to monotonically increase with the decrease of V_b. This result really indicates that the extrapolation of asymmetries can still be applicable to the Mott spin polarimeter with such special retarding optics.

A phenomenon was found for small energy loss windows. It was observed that the scattered electrons can penetrate through the CL and PG assemblage even at $V_b=0$. This phenomenon can be understood from the finite small spacing between the PG wires. In our retarding optics, the distances from the PG to the front side of MCP and the inner sphere are 3.7 and 12 mm, respectively, and the spacing of the PG grid is 0.85 mm, not small enough to block the stray electrical field from the MCP and inner sphere even when V_b is zero. This is confirmed by further simulation. In Fig. 4, the electrical potential along the axis of the retarding optics was calculated by an electron optics program code.[11] In the simulation, four plates at $z=-12$, -6, 0, 3.7 mm represent IS, OS, PG, and the front end of MCP, respectively. Two holes with diameters of 26 and 0.85 mm are opened on OS and PG plates around the optics axis. The biases on IS, OS, PG, and

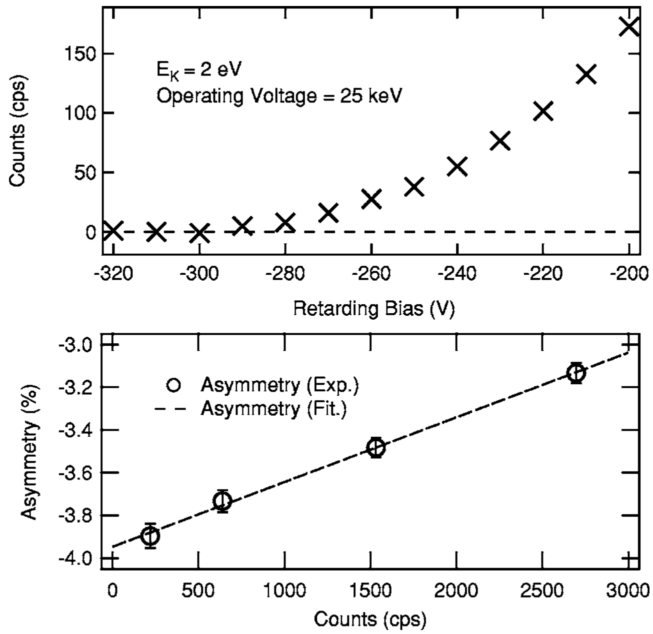

FIG. 5. (a) The scattering intensity $I(=N_L+N_R)$ as a function of V_b, the bias at the cylindrical lens and the plane grid of the electron optics. (b) The observed scattering asymmetry A vs I for 25 keV electrons.

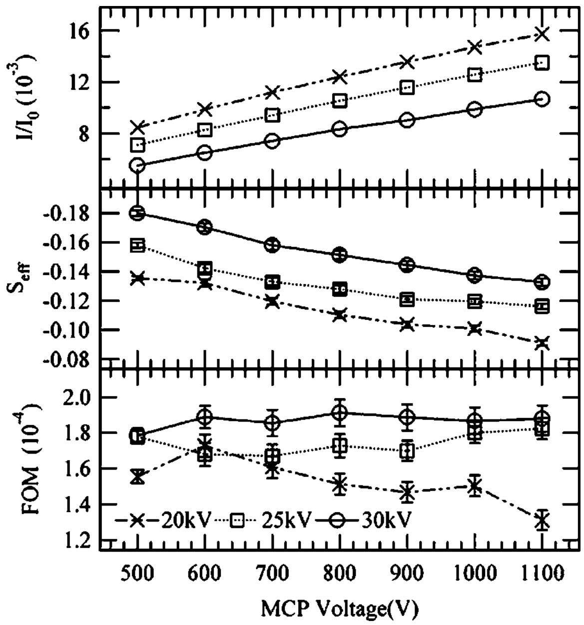

FIG. 6. (a) The normalized scattering intensity (I/I_0), (b) the effective Sherman function (S_{eff}) and (c) the FOM of our Mott spin polarimeter for a different front bias of MCP (V_{in}) at 20, 25, and 30 kV operating voltages. The error bars only show the statistic error and its value of I/I_0 is too small to be seen.

MCP plates are set as 25 000, 0, 0, and 500 V, respectively. We can see that the minimum potential along the axis is not zero but 115 V. It indicates that the exact condition for $\Delta E_{\text{loss}}=0$ can be achieved not at $V_b=0$ but at a certain negative voltage of V_b. In order to determine the value of V_{b0} corresponding to $\Delta E_{\text{loss}}=0$, we have measured the sum I of the electron count rates of the left and right MCPs vs V_b at 25 keV operating energy [Fig. 5(a)]. We find that the I reaches zero around $V_b=-300$ V. The value of V_{b0} should be very close to this value if we take into account the less-than-3 eV energy resolution of the retarding field as discussed by Gay.[7] It seems, however, difficult to assign the adequate V_{b0} from the I-V_b plot. To solve this problem, we extrapolated A to zero I, as it should be equal to that extrapolated to zero ΔE_{loss}. A plot of A vs I was made as shown in Fig. 5(b). It is clear that the magnitude of asymmetry A decreases linearly with I, which can be fitted with a function $A=A_0+CI$ (dashed line) with $A_0=-0.0395\pm0.0004$ and $C=(3.0\pm0.3)\times10^{-6}$ (in the expression, only the statistical error is included). With this relation, we can extrapolate the scattering asymmetry to zero I ($\Delta E_{\text{loss}}=0$) as -3.95%. Consequently, the spin polarization P of the secondary electrons can be evaluated as 14.4% using $S_0=-0.275$, the reported effective Sherman function at zero ΔE_{loss} for 25 keV electrons.[8]

Next, we will show the estimation procedure of S_{eff} and FOM at the actual condition of spin-resolved photoemission experiments. In this case, the ΔE_{loss} was set by the front bias of the MCP, while the voltages applied to the CL and the PG were kept at 3000 V for optimal performance of electron optics for the scattered electrons. With the experimental A, we estimated S_{eff} with the formula $S_{\text{eff}}=A/P$. Here $P=14.4\%$ was used as determined above. The incident electron current (I_0) has been measured by the S-MCP inserted into L3. The observed I/I_0, S_{eff}, and corresponding FOM with V_{in} in the range of 500–1100 V at 20, 25, and 30 kV operating voltages are shown in Figs. 6(a)–6(c). The operating parameters of maximum FOM for 20, 25, and 30 kV operating voltages are shown in Table I. The overall maximum FOM of 1.9×10^{-4} (corresponding $S_{\text{eff}}=-0.15$) has been achieved at $V_{\text{in}}=800$ V and 30 kV operating voltage.

IV. SUMMARY

In summary, we have developed a retarding-type Mott spin polarimeter for the spin- and angle-resolved photoemission experiments at Hiroshima Synchrotron Radiation Center (HSRS). We have illustrated how to evaluate S_{eff} and FOM by a self-calibration method for this Mott polarimeter with a special retarding optics. The maximum efficiency of our Mott polarimeter was found as 1.9×10^{-4} with S_{eff} as -0.15 when V_{in} and operating voltage were 800 V and 30 kV, respectively.

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TABLE I. The maximum values of FOM and corresponding S_{eff}, I/I_0, and V_{in} for 20, 25, and 30 kV operating voltages.

Target voltage	V_{in}	S_{eff}	I/I_0	FOM
20 kV	600 V	−0.13	9.9×10^{-3}	1.7×10^{-4}
25 kV	1100 V	−0.12	1.3×10^{-2}	1.8×10^{-4}
30 kV	800 V	−0.15	8.3×10^{-3}	1.9×10^{-4}

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