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PROJECTING CLASSICAL MOTT POLARIMETER

V.N. Petrov[1], **P.G. Gabdullin**[1], **A.V. Pavlov**[1],
A.B. Ustinov[1], **V.N. Strocov**[2], **J.H. Dil**[2]

[1] Peter the Great St. Petersburg Polytechnic University,
St. Petersburg, Russian Federation;

[2] Paul Scherrer Institute,
Brugg, Switzerland

In this paper we describe a new spin detector designed and manufactured at SPbPU. This device makes it possible to analyze the polarization of the secondary electron flux conserving the information about the electrons' spatial distribution. The main stages of development, construction and testing the detector are discussed in details. As a result, the possibility of implementing such devices has been proved in principle. At the same time, both high spatial resolution of this device and its efficiency were demonstrated. Combining such detectors with hemispherical energy analyzers will make it possible to obtain spin-resolved dispersion images of the structure under study.

Keywords: Mott detector, spin, electron spectroscopy, secondary electron polarization

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ПРОЕКЦИОННЫЙ КЛАССИЧЕСКИЙ ДЕТЕКТОР МОТТА

В.Н. Петров[1], **П.Г. Габдуллин**[1], **А.В. Павлов**[1],
А.Б. Устинов[1], **В.Н. Строков**[2], **Ж.Х. Дил**[2]

[1] Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация;

[2] Институт Пауля Шеррера,
г. Бругг, Швейцария

В работе описывается новый спиновый детектор, разработанный, сконструированный и изготовленный в СПбПУ. Такой прибор позволяет анализировать поляризацию потока вторичных электронов, сохраняя информацию об их пространственном распределении. Представлены основные этапы создания и тестирования разработанного устройства, продемонстрированы результаты испытаний его отдельных узлов. В результате доказана принципиальная возможность реализации подобных устройств. При этом продемонстрированы как высокое пространственное разрешение данного прибора, так и его эффективность. Совмещение таких детекторов с полусферическими энергоанализаторами современных электронных спектрометров позволит получать спин-разрешенные дисперсионные зависимости исследуемой структуры.

Ключевые слова: детектор Мотта, спин, электронная спектроскопия, поляризация вторичных электронов

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Introduction

The spin configuration of a certain ensemble of particles is important for describing many physical processes and phenomena. A physical quantity known as polarization P is used to characterize the experimentally measured spin structure. Polarization relative to a specific quantization axis follows the expression

$$P = (N^{\uparrow} - N^{\downarrow})/(N^{\uparrow} + N^{\downarrow}),$$

where $N^{\uparrow}$, $N^{\downarrow}$ are the numbers of electrons with spin parallel or antiparallel to quantization axis, respectively. The projection of spin can take values $+\hbar/2$ and $-\hbar/2$.

The spin degree of freedom can be used to describe a variety of physical phenomena. The results of spin measurements made a major contribution to understanding such physical phenomena as giant magnetoresistance [1], formation of magnetic domains [2, 3], Rashba effect [4], and appearance of topologically protected states in solids [5].

Polarization of particle fluxes can be detected directly, for example, by using the classical Mott polarimeter [6, 7]. Electrons in such a device are accelerated to energies of the order of 40 – 100 keV, and subsequently scattered by gold foil. Due to spin-orbit interaction, a spin-dependent scattering occurs on the gold foil, allowing electrons with a spin projection parallel to the the quantization axis to be slightly more probably scattered into one of the detectors, and electrons with an opposite spin projection to the other.

The resulting scattering asymmetry A can be expressed as

$$A = (N_1 - N_2)/(N_1 + N_2),$$

where N_1, N_2 are the numbers of electrons captured by the first and second detectors, respectively.

Since the potential of the spin-orbit interaction depends linearly on spin projection, it can be assumed that asymmetry is proportional to the polarization value, i.e., $A \sim P$. This allows calculating the polarization as follows: $P = A/S$, where S is the Sherman function. The value of Sherman function is determined by the false asymmetry arising from imperfection of the experimental setup.

Angle-resolved photoemission spectroscopy (ARPES) is an important modern experimental technique [8]. Using this method, it is possible to obtain angle-resolved secondary electron spectra emitted from a sample [8]. Since the emission angle of electrons in a solid is related to the value of electron momentum, ARPES can be used to directly measure the electronic band dispersion for electrons $E(\mathbf{k})$ (E is the electron energy, $\mathbf{k}$ is the wave vector).

The available devices typically operate as follows: the secondary electrons are emitted from the sample, then fall to the energy analyzer, where they are separated by their energy and entrance angle. The electron flux is then amplified by means of a microchannel plate. After passing the microchannel plate, the electrons fall on the fluorescent screen, where they are converted into visible radiation subsequently recorded by a camera outside the vacuum chamber.

Such energy analyzers allow simultaneous measurement of the number of particles, their momenta and energies in a wide range, thus significantly reducing the time required to accumulate data. A hemispherical energy analyzer used in ARPES in combination with a Mott polarimeter makes it possible to experimentally measure spin and angle-resolved electronic dispersion (SARPES) [9]. This method serves as an indispensable tool for studying new materials.

A serious drawback of available SARPES devices is that the existing Mott polarimeters are single-channel devices, which means that only a small portion of the secondary electron flux is recorded at each moment in time, with the energy and momentum projection in a narrow range. This outweighs the potential benefits that spatially sensitive energy analyzers could provide. This fact significantly reduces the effectiveness of the experiments conducted.

This problem may be solved using a Mott polarimeter which combines spin analysis with the spatially sensitive electron detectors. The first proposal for such a device was presented in [10]. In this work, we describe process of creating and testing a multichannel polarization detector based on the classical Mott polarimeter.

Design and development

The multichannel polarization detector was developed based on the classical Mott polarimeter, with changes introduced to ensure spatial resolution.

Fig. 1 shows a schematic representation of the Mott polarimeter constructed. The construction allowed for assembling the device right after the exit aperture of the PHOBOS 150 hemispherical energy analyzer (by SPECS, Germany).

The device operates as follows. After passing through the energy analyzer, the electron flux propagates through the entrance aperture *1* of the Mott polarimeter. Then the electron flux passes through a focusing four-section electrostatic lens *2*. The focused electron beam is then accelerated by a 40 kV potential and enters drift space *3*. This beam can then scatter either on the CCD matrix or gold foil *5* (this is selected by turning the vacuum manipulator).

The first mode (the CCD matrix is in the center of the detector) is required to adjust the electro-optical lens of the detector. The image is obtained by the CCD matrix located at the center of detector, right after electrostatic lens (Fig. 2). In the second mode, electrons are scattered by gold foil. In this case, due to spin-dependent scattering on the gold foil, the electrons have a

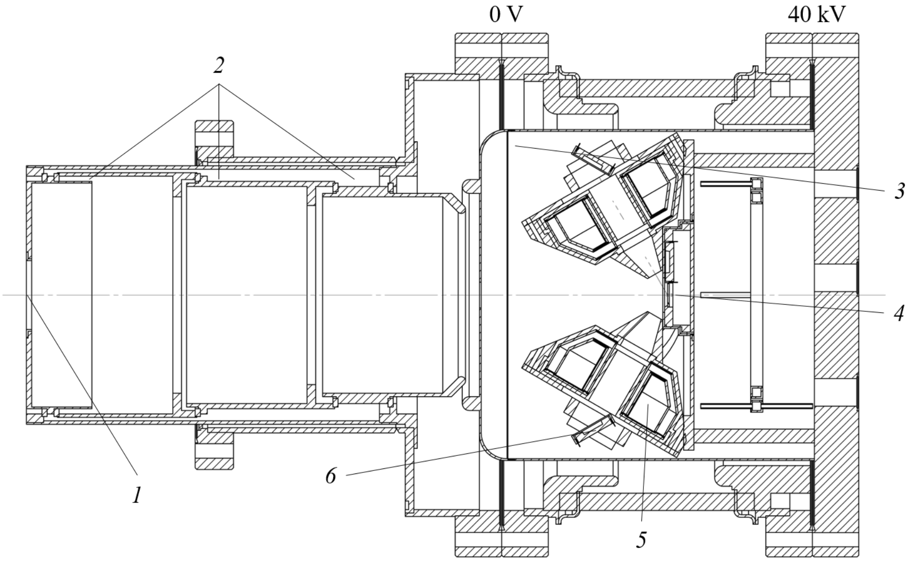

Fig. 1. Scheme of multichannel Mott polarimeter:
1: entrance aperture, *2*: focusing electrostatic lens, *3*: electrostatic screen, *4*: gold foil (or CCD matrix), *5*: magnetic lens, *6*: CCD array. The captions ‘0 V’ and ‘40 kV’ correspond to the potentials applied to the respective parts of the device

higher probability of falling into one of four detectors depending on spin orientation (two detectors for each spin projection). Thus, the device is capable of analyzing the polarization of the electron flux.

After scattering on gold foil, the electrons enter the detector, which consists of a magnetic focusing lens (position *5* in Fig. 1) and CCD matrix *6*, which is capable of detecting high-energy electrons. The magnetic lens is designed to focus the scattered electrons, and the matrix serves as a detector recording not only the arrival of the particle but also the position of the pixel that captures it. Hamamatsu S7170 sensors (Japan) were chosen as the detector, as they have neither a protective layer nor an ultraviolet filter, which allows them to effectively detect high-energetic charged particles. Thus, the device records collision events between accelerated secondary electrons and the CCD matrix. Figs. 2 and 3 show images of the aperture located inside the energy analyzer, obtained on a CCD array in secondary electron counting mode. The size of each pixel (px) in such an array is 24 μm × 24 μm, its resolution is 512 px × 512 px.

So, such device consequently would not only be capable of spin analysis of the electron flux but can also detect the electrons' spatial distribution. In particular, it can measure the spin-resolved electron dispersions $E(\mathbf{k})$.

Testing and calibration of the Mott polarimeter

Construction of a device is a complex process comprising several stages and procedures such as making drawings of the device, manufacturing, welding and assembling its componentss, conducting vacuum tightness tests. A series of tests is then carried out for dielectric strength for the insulators that are used in the detector.

In a device which functions correctly, the electron flux is supposed to be focused on the gold foil without any distortion, then the electron flux reflects from the foil focused and then collected on the CCD matrix. Since each point in the cross section of the electron beam carries information about the physical properties of the given sample, the level of distortion should be kept to a minimum.

To adjust the electrostatic and magnetic optics, a plate with a pattern made up of holes 0.50 and 0.25 mm in diameter was placed inside the energy analyzer. After electrons passed through the energy analyzer, they were distributed in space in accordance with their energy and emission angle. Traveling through the aperture, this electron flux was converted into an image of a point array, where inside each point the electrons had similar energies and emission angles.

A CCD matrix was installed in the center of the Mott polarimeter (instead of the gold foil) to test the electrostatic lens. An example of an image obtained in secondary electron counting mode is shown in Fig. 2. Here the X axis is parallel to the direction along the energy axis of the analyzer, and the Y axis is parallel to the direction along which the emission angle of electrons in the beam was measured. A sharp image of the aperture on the CCD matrix corresponds to optimal focusing of the electrostatic lens. Adjusting the electron optics and changing the accelerating voltage made it possible to choose an amplification factor of the lens suitable for the experiment.

After a sharp image was obtained on the CCD matrix in the center of the Mott polarimeter, the voltages at the electrodes of the electrostatic lens were recorded, and gold foil was installed in the center of the polarimeter.

The magnetic lenses were adjusted by varying the value of the current flowing through the coils. This current generates a magnetic field where the electron trajectories are twisted around the axis of the lens. This provides the required focusing, but inevitably produces some distortion to the image.

Fig. 3 shows images of the aperture on the CCD matrix located behind the magnetic lens. The im-ages on the left and right arrays of the Mott polarimeter should be rotated in different directions if the direction of current is the same in both lenses. Slight blurring of the images is due to the aberrations in the complex electron-optical system, and they can be further minimized by finer adjustment of the optics and image post-processing.

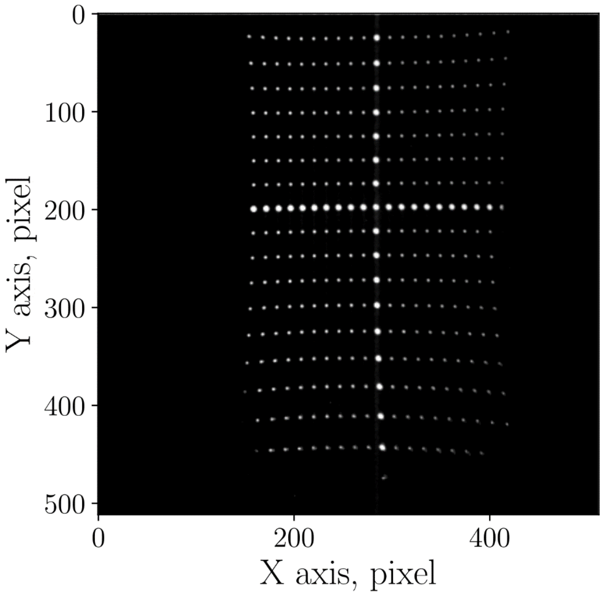

Fig. 2. Images of aperture inside the energy analyzer taken on the CCD matrix
in the center of the Mott polarimeter.

The intensity at each point is proportional to the number of electrons hitting a given pixel of the matrix The background corresponding to the dark current of the CCD matrix and illumination from inelastic electrons was subtracted from the image

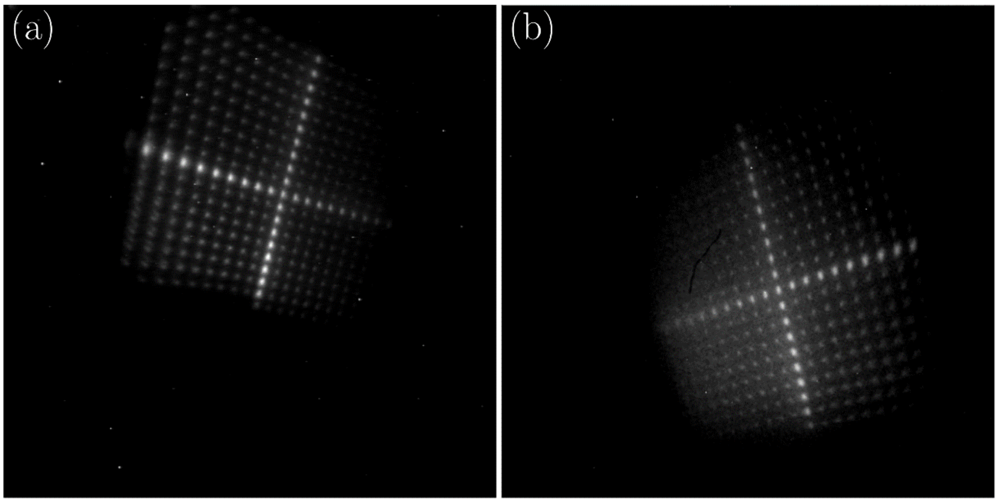

Fig. 3. Images of the aperture installed in the same location as in Fig. 2 but obtained on the first (*a*) and the second (*b*) CCD detectors behind the magnetic lenses (see also explanations to Fig. 2)

As the last test of the system, we measured the asymmetry of electron beam from a magnetized sample by the Mott polarimeter. An amorphous iron boride (FeB) sample has been chosen as a magnetic target. As a soft magnetic with a rectangular hysteresis loop, this material has stable surface magnetism, which makes it convenient for experiments. The sample was irradiated with a beam of primary electrons, while the flux of secondary electrons was directed to the energy analyzer to determine the energy dispersion, and then into the Mott polarimeter for spin analysis.

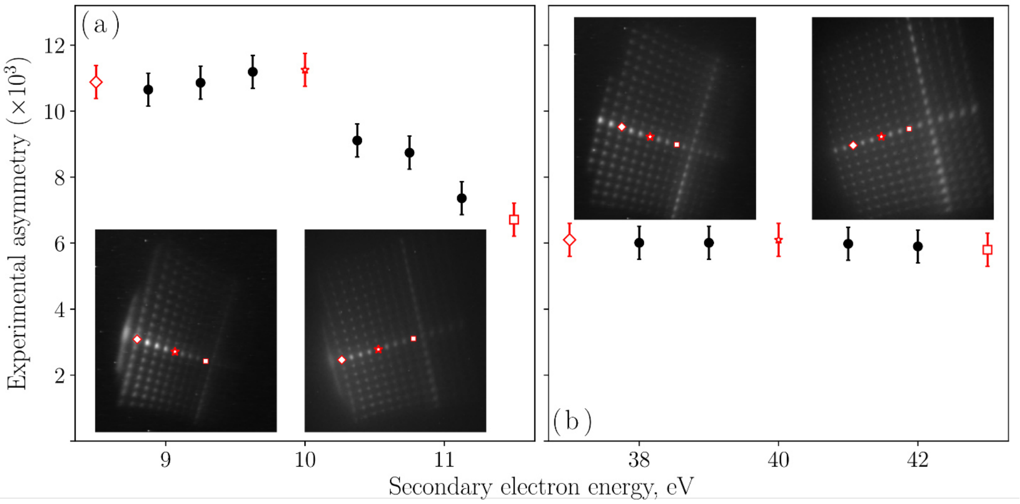

Fig. 4. Asymmetry of electron flux depending on the energy of low- (*a*) and high-energy (*b*) secondary electrons emitted from a magnetized FeB sample (measurements were carried out by a Mott polarimeter). The insets show images from two CCD matrices (see Fig. 3), where diamonds, stars and boxes mark the points serving as the sources of the signal used to calculate the asymmetry (marked with the same symbols on the graphs)

Fig. 4 demonstrates the dependencies of asymmetry on the energy of secondary electrons for two energy ranges: 8.5 – 11.5 and 37 – 43 eV (central values of energy are 10 and 40 eV, respectively). As noted above, the electron flux is converted into a point array by aperture as it passes through the energy analyzer. In this case, the electrons inside each point have close values of energy and similar emission angles. This can be used to obtain the asymmetry of the electron beam as a function of energy. The empty symbols in Fig. 4 correspond to the points whose signal level (see images in the inset) was used to calculate the asymmetry. Analyzing the data in Fig. 4, we can conclude that low-energy electrons have higher polarization compared to higher-energy ones, which is in good agreement with the literature data [11, 12].

Further experiments will allow to find find the value of the Sherman function S for this Mott polarimeter. After all calibration and adjustment procedures, it will be possible to measure the spin-resolved electronic band dispersions.

Conclusions

In this paper, we present the details of the process of creating and testing a novel prototype of a classical projecting Mott polarimeter. Individual units of the device have been tested at various construction stages.

While the final adjustments remain to be introduced before the device can be put into operation, it has been established that implementing such devices is possible in principle. High spatial resolution of this device and its efficiency have been confirmed.

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THE AUTHORS

PETROV Vladimir N.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
petrov@physics.spbstu.ru

GABDULLIN Pavel G.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
gabdullin_pg@spbstu.ru

PAVLOV Alexander V.
Alferov University of RAS
8-3 Khlopin St., St. Petersburg, 194021, Russian Federation
a.pavlov@physics.spbstu.ru

USTINOV Alexander B.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
ustinov@physics.spbstu.ru

STROCOV Vladimir N.
Paul Scherrer Institute
111, Forschungsstrasse, Villigen PSI, 5232, Switzerland
vladimir.strocov@psi.ch

DIL Jan Hugo
Paul Scherrer Institute
111, Forschungsstrasse, Villigen PSI, 5232, Switzerland
jan-hugo.dil@psi.ch

СПИСОК ЛИТЕРАТУРЫ

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СВЕДЕНИЯ ОБ АВТОРАХ

ПЕТРОВ Владимир Никифорович – *доктор физико-математических наук, профессор кафедры физики Института физики, нанотехнологий и телекоммуникаций Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29
petrov@physics.spbstu.ru

ГАБДУЛЛИН Павел Гарифович – *кандидат физико-математических наук, доцент Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29
gabdullin_pg@spbstu.ru

ПАВЛОВ Александр Валерьевич – *преподаватель кафедры общей физики Санкт-Петербургского национального исследовательского академического университета имени Ж.И. Алфёрова РАН, Санкт-Петербург, Российская Федерация.*

194021, Российская Федерация, г. Санкт-Петербург, ул. Хлопина, 8, к. 3
a.pavlov@physics.spbstu.ru

УСТИНОВ Александр Борисович – *кандидат физико-математических наук, доцент Высшей инженерно-физической школы Санкт-Петербургского политехнического университета Петра Великого, Санкт-Петербург, Российская Федерация.*

195251, Российская Федерация, г. Санкт-Петербург, Политехническая ул., 29
ustinov@physics.spbstu.ru

СТРОКОВ Владимир Николаевич – *доктор физико-математических, наук, научный сотрудник Института Пауля Шеррера, г. Бругг, Швейцария.*

5232, 111, Forschungsstrasse, Villigen PSI, Switzerland
vladimir.strocov@psi.ch

ДИЛ Жан Хьюго – *PhD, глава научной группы COPHEE Института Пауля Шеррера, г. Бругг, Швейцария.*

5232, 111, Forschungsstrasse, Villigen PSI, Switzerland
jan-hugo.dil@psi.ch