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Trevor Hicks and solid state neutron optics

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Abstract
Following an idea of Trevor Hicks we built neutron polarizing benders with silicon wafers forming the bender channels. In the last decade a variety of neutron optical devices based on this idea were realized such as collimators with absorbing as well as reflecting walls, radial benders and collimators and focusing devices which are all much shorter than their classical counterparts. Their development will be reviewed here.

1. Introduction

At the beginning of the 1990s Trevor Hicks spent a sabbatical year at our institute, formerly named the Hahn–Meitner-Institut Berlin. At that time we had started producing polarizing neutron supermirrors with 100 layers made from a FeCo alloy and Si. Trevor observed these activities with great attention because he saw a chance to realize his old idea of a polarizing bender with channels formed by thin silicon wafers. In the following years we succeeded in producing such devices in cooperation with him. As it turned out, this device was just the first step in a whole series of neutron optical devices based on silicon wafers. The development of these solid state neutron optical devices will be reviewed here.

2. Polarizing benders

2.1. Solid state bender

After the invention of the first polarizing benders with air gaps and Co–Ti supermirrors built by Schärpf [1] the groups at PSI [2] and PNPI [3] have also produced such devices. They consist of bent boron-glass plates coated with an anti reflection layer and polarizing supermirrors. Since the glass thickness amounts to 0.2 mm or more the channels usually have a thickness of 0.5–1 mm leading to a total length of 0.3–1 m, depending on the desired critical wavelength.

Trevor's idea was to replace the air channels by silicon wafers which can have a thickness of only a few tenths of an mm. Following his idea such systems were built by Majkrzak [4] and by our neutron optics group in Berlin [5].

The bender consisted of single side polished Si wafers with 75 mm length, 50 mm width, and 0.25 mm thickness which were coated on one side with $m = 2$ FeCo–Si supermirrors and on the other side with Gd. Here m gives the ratio of the supermirror critical angle to that of natural nickel. Typically 100 wafers were put together into a bender with their middle deflected by one wafer thickness to close the direct line of sight. Thus the spin up neutrons were reflected by the bent supermirror coated side and could leave the wafer while the spin down neutrons passed the coating and were absorbed in the Gd layer of the next wafer, cf figure 1.

The maximum transmission achieved with this bender at a wavelength of 4.7 Å for the spin up component was 71%; the average value over 2000 wafers was 61%. The theoretical limit for the transmission was in this case 74%. If the bender is rocked in the beam with the wafers essentially perpendicular to the scattering plane the transmitted intensity shows a distribution which has a full width at half maximum (FWHM) of 0.75° in the rocking angle. The mean flipping ratio was $f = 47$ corresponding to a polarization $P = (f - 1)/(f + 1)$ of 96%. In the direction parallel to the wafers a large angular range of 5°–25°, depending on the distance from the sample, can be analyzed.

At ANSTO, the Australian institute running at that time the research reactor HIFAR, Trevor wanted to improve the neutron spin polarization and analysis of the instrument LONGPOL, which operated at a neutron wavelength of 3.6 Å. It had previously used iron filters with a flipping ratio of 3. In a cooperation between our institutes we provided coated wafers for one polarizing bender with a cross section of 25 mm × 50 mm and eight analyzers each with a cross section of 25 mm × 100 mm [6], which allowed the flipping ratio to be increased to 47.

Ten years later the neutron optics group at the HZB in Berlin now uses double side polished wafers with a thickness of 0.15 mm and coatings of polarizing supermirrors with $m = 3$, which allows polarization of neutrons with wavelengths down

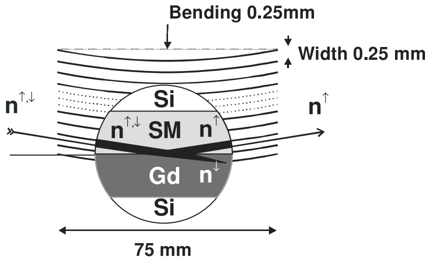

Figure 1. Schematic view of the polarizing bender with Si wafers as channels. They have a width of 0.25 mm and are coated on one side with a polarizing FeCo–Si supermirror and on the other side with a Gd layer.

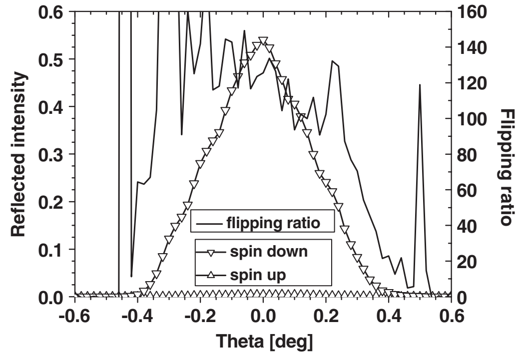

Figure 2. Rocking curve for the neutron intensity transmitted through the transparent bender discussed in section 2.2 for both spin states together with the flipping ratio. (Neutron wavelength 0.48 nm.)

to 2 Å and a divergence of $m = \pm 2.5$ with a transmission of 50% of the spin up component and a polarization of 96%–98%. Several such benders are now in use worldwide.

2.2. Transparent bender

Benders traditionally contain absorbing layers: the glass and the anti reflecting layer, which absorbs the unwanted spin state which otherwise would be reflected from the glass at small angles in the classical benders, and the Gd layers in the solid state bender. While in a classical bender the glass is the indispensable substrate material for the supermirror, a solid state bender can be built without absorbing layers and then transmits both spin components working as a spin splitter. Inserted into an unpolarized neutron beam such a device transmits the spin down component without any change in its flight path and reflects the spin up component. By setting a collimator in the direction of one of the two spin components only this one will be transmitted.

Such a device for neutrons with a total length of less than 9 cm and for wavelengths above 4 Å was built and tested [7]. It consists of a stack of thin silicon wafers coated on one side with FeCo–Si supermirrors with $m = 2.3$. In a holder, 125 of these wafers were bent and subjected to a magnetic field of 1 kG.

The collimator was also built from silicon wafers, which were coated with a Gd layer, cf section 3.1. Collimator and bender both cover a beam cross section of 50 mm × 20 mm.

Figure 2 shows the rocking curve for the combined system of bender and collimator normalized to the direct beam. Bender and collimator were set at the angle of maximum transmission and the whole system was rocked in the beam.

The collimator determines the FWHM. The transmission reaches a maximum of 54%. The flipping ratio is above 100 for most of the angular range; its mean value weighted with the transmitted intensity is 129.5. The corresponding polarization values are 98.0% and 98.5%.

This transparent bender combines the short length of a bender with the advantage of a transmission polarizer which retains the neutron paths. As a bender it has no traditional analogue.

2.3. Radial bender

Conventionally large arrays of supermirrors or ^{3}He polarizers are used to polarize or analyze the spin of a divergent neutron beam,

A similar result can be accomplished by a solid state radial bender which is similar to the solid state bender but has channels consisting of one or more wafers, which are inclined to each other by spacers but form a continuous area at the front side [8]. The polarizing efficiency of a ^{3}He polarizer does not depend on the divergence of the neutron beam whereas a radial bender polarizes or analyzes at each position in space only that angular range given by its supermirror coating. It achieves a large angular range by changing the angle of its acceptance range with position. Thus it only covers the full divergence of a point or slit source and not that of an area source like a guide. For many experiments this is sufficient.

Rocking the radial analyzer in the beam with the wafers perpendicular to the scattering plane, an angular range of 3.6° was spin analyzed in the scattering plane; this is much larger than the critical angle of the supermirrors used which amounted to only 0.95° at 4.7 Å. In the direction parallel to the wafers a large angular range of 9.5° could be analyzed. Thus a solid state radial bender allows a two dimensional spin analysis over large angular intervals.

2.4. S-bender

In the latest variety of the solid state bender the neutrons are reflected twice during passage through a channel which is bent in S-shape [9]. This allows a polarization of 98% or more to be achieved but due to the increased length the losses in the silicon are higher. The advantage of this set up is that the transmitted beam is parallel to the incoming one, thus facilitating the experimental set up if it is used in both polarized and unpolarized modes.

3. Collimators

3.1. Solid state collimators

Neutron collimators are mostly built from plastic or steel foils which are coated with an absorbing layer of Gd_2O_3 in a resin.

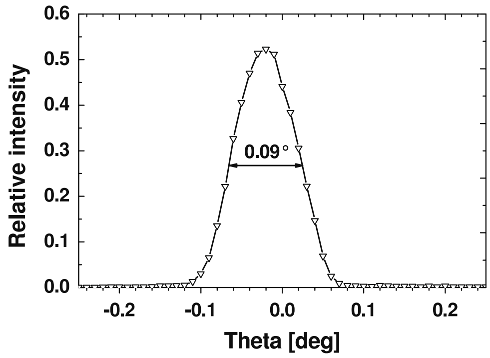

Figure 3. Rocking curve for the neutron intensity transmitted through a solid state collimator with absorbing walls and channels of 0.1 mm width and 80 mm length.

These walls have a typical thickness of 0.1 mm. The collimator length is of the order of 300 mm. Here as for the classical polarizing benders a minimum channel width of 0.5–1 mm is necessary to reduce the relative losses due to the cross section of the walls.

In analogy to the benders, we developed collimators using silicon wafers as channels which are sputter coated with a Gd layer. It could be experimentally shown for the first time that they behave as proper collimators [10]. Such a device with a FWHM of 0.3° was used for the transparent bender described above. Recently we built a collimator with a collimation of only 0.09°. It has channels with a width of 0.1 mm and a length of 80 mm and was rocked in a neutron beam with a wavelength of 4.9 Å, as shown in figure 3.

3.2. Collimators with reflecting walls

The well polished surface of thin silicon wafers opens up another fascinating, though until now not used option: collimators which reflect neutrons up to a wavelength dependent critical angle.

Collimators with absorbing walls have a triangular transmission function with a FWHM of $\Theta = \arctan(d/l)$, where d is the thickness and l the length of a channel. The base width is 2Θ. Using Si wafers one can coat the channel walls first with a reflecting material with a critical angle of reflection Θ_c and then with an absorbing layer. This leads to a rectangular transmission function with a base width of $2\Theta_c$. With ideal mirrors, and neglecting attenuation in silicon, one finds that the transmitted intensity increases by 100% within the angle interval of $2\Theta_c$ compared to a collimator with purely absorbing walls. The full advantage of these devices can be exploited if two or more such collimators are used in series, as in a triple axis instrument. For two collimators in series the intensity gain offered by an ideal rectangular transmission is a factor of 2.16 for equal resolution compared to a triangular transmission.

The idea of using reflecting walls for a collimator was proposed as early as 1956 by Sailor *et al* [11], a principle which is also used in the polarizing cavity [12] and which was again discussed by Cussen [13]. It was realized by our group [14] and by Cussen [15]. We used silicon wafer channels with a width of 0.52 mm and a length of 75 mm coated either with Gd, or 2000 Å FeCo, or an $m = 2$ FeCo–Si supermirror.

The experimental results showed that a reflective coating on the channel walls of a collimator improves the transmission as expected, compared to a traditional Soller type collimator with the same base width. It should be mentioned that the coating can only be perfectly matched to the geometrical transmission of the equivalent Soller collimator for one wavelength. The distribution of the transmitted neutrons gradually changes for smaller wavelengths from a rectangular shape to a triangular one, while for larger wavelengths λ it remains rectangular with its FWHM increasing with Θ_c and exhibiting a constant FWHM/λ ratio. This property might be useful e.g. for reflectometers at a spallation source.

3.3. Radial collimators

Radial collimators with absorbing walls were built for a small angle scattering instrument as part of a transparent bender [16]. They collimated the beam to the detector in a distance of 1.8 m. The FWHM of the incoming neutron beam was 0.6° and the FWHM of the collimated beam was 0.23°, leading to a penumbra with a diameter of 14 mm.

Radial collimators can also be built with reflecting walls. Wafers with the same coatings as used for the reflecting collimators described above were employed to build a radial collimator [17]. Here the supermirror coated collimator channel was opened at the downstream end by inserting a thin slab of a silicon wafer with a width of 0.52 mm at a distance of 40 mm from the front side.

A radial collimator has a trapezoidal transmission function with respect to the angles. The width of the roof of the trapezium with a transmission of 100% is given by the opening angle of the collimator walls, which was for our device ±0.37°. The angle at the base line is the maximum angle under which neutrons can pass the collimator without touching a wall, this was ±0.77°.

Experimentally it was found that neutrons with a wavelength of 4.7 Å were reflected from the walls up to 1°. Due to the wall inclination of ±0.37° neutrons are transmitted up to ±1.37°. Compared to a conventional radial collimator neutrons scattered from a larger sample area are transmitted.

4. Focusing device

In recent years a strong activity has developed in the field of neutron focusing. To enhance the neutron flux at the sample position, neutron beams can be focused while their divergence correspondingly increases according to Liouville's theorem. Several neutron scattering techniques can benefit from neutron beams focused in both dimensions, such as prompt-gamma analysis, tomography, neutron depth profiling and more generally experiments with small samples such as protein crystals or samples under high pressure. Other techniques, for example reflectometry, can use focusing in one dimension.

In 1990 Mildner proposed a stack of bent wafers where the neutrons are guided in thin silicon channels with reflecting

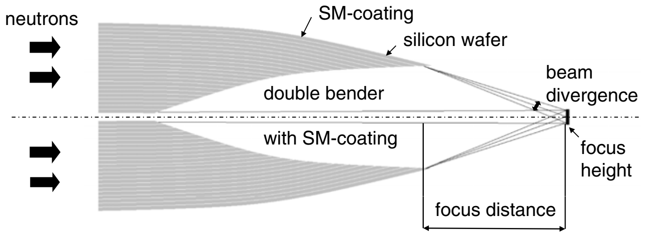

Figure 4. Schematic view of a focusing lens with Si wafers as channels. They have a width of 0.15 mm and are coated on one side with an $m = 2$ Ni–Ti supermirror. The lens accepts a divergence up to $m = 2$ and achieves a gain of 5.6 in the focus.

walls [18]. Their length increases with increasing distance from the beam axis in such a way that all neutrons leaving a wafer are focused onto the same focal spot. This device accepts all neutrons with a divergence below the critical angle of the wafer coating and is achromatic since it employs reflection. At that time such a device was not realized.

As shown in figure 4 we built a symmetric lens made up of two stacks with a total cross section of 20 mm × 30 mm and wafer lengths up to 140 mm [19]. The wafers were single side coated with Ni–Ti supermirrors with $m = 2$ and stacked in a holder which bends them to a circular shape.

The lens was placed in front of a 2D detector in a neutron beam with a wavelength of 5.0 Å, a cross section of 48 mm × 32 mm, and a divergence of 0.6°.

The highest intensity was found at the focal spot 31 mm behind the end of the lens. Perpendicular to the beam it had a nearly Gaussian shape with a FWHM of 2.4 mm and the peak intensity was 5.6 times larger than the direct beam at this spot without the lens. In addition, along the flight path of the beam, the intensity distribution shows a maximum at the focal point and has a FWHM of 50 mm which strongly facilitates the adjustment of the lens relative to a sample.

5. Summary

Solid state neutron optical elements show geometrical advantages compared to their conventional counterparts:

Firstly the size can be very small; e.g. a polarizing bender can be 100 times shorter than a cavity for a 60 mm wide neutron beam. Collimators are shorter by a factor of 5–10; e.g. a 10 min of arc collimator built with wafers of 0.1 mm thickness has a length of 35 mm. This also leads to a lower weight.

Secondly the excellent geometrical definition of the wafers allows the use of a simple mechanical design which introduces only small deviations from the optimum geometry and is less expensive. As a result good flipping ratios are achieved. If very thin Si wafers below 0.1 mm thickness become available at reasonable prices it can be expected that the solid state benders could work down to wavelengths of 1 Å and that collimators could achieve collimation better than 5 min of arc.

Thirdly neutron propagation through silicon offers important advantages. In benders the anti reflection layer between the substrate and supermirror can be omitted. Collimators can have additional reflecting layers. Obviously, solid state elements need no extra walls as support for the coating, thus the full cross section can be used except for about 1 μm per wall for the coating, while for conventional benders at least 0.2 mm and for collimators at least 0.1 mm per wall are lost.

The physical properties of the channel determine the neutron losses. They are negligible for traditional elements with air or vacuum gaps but limiting for the solid state elements. The neutron losses in silicon are determined for wavelengths above 3 Å mainly by nuclear absorption, which increases with $1/v$, while for smaller wavelengths phonon scattering leads to an increase of the losses [20]. For the wavelength range 1.5–3 Å the loss is minimal and amounts to 2% cm^{-1} of silicon. The corresponding figures are 4% cm^{-1} for 0.9–1.5 Å and 3–7 Å and 6% cm^{-1} for 0.65–0.9 Å and 7–10 Å. The length of solid state elements is determined by the channel thickness and the critical angle of the coating; usually it is below 10 cm.

6. Conclusion

From this short historical overview it is evident that Trevor Hicks' idea to use silicon channels for a polarizing bender proved to be very fruitful. It truly opened up a new chapter in the design of neutron optical devices and allowed the building of smaller and better instruments.

For the whole community devoted to the improvement of neutron instrumentation, and especially for the Berlin group of neutron optics, I want to express my deep thanks to Trevor.

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