Submicron structures - promising filters in EUV. A review

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ABSTRACT

A novel, fledgling approach to the filtering of EUV radiation for laboratory and space applications is reviewed. Foils perforated by a set of parallel channels with submicron diameters serve as wavelength dependent filters. Each channel passes photons when the wavelength is much smaller than the channel diameter. The transmission of the channel drops dramatically, however, when the wavelength becomes comparable to or larger than the channel diameter. The relevant theoretical considerations as well as available experimental data are presented. Several different ways to manufacture such kind of filters are outlined, including nuclear track filters, anodized metal films, and microchannel plate technology. Advantages and disadvantages of each technique are discussed. The history of the work in the field as well as prospects for the future are presented.

1. INTRODUCTION

Filtering the radiation in the EUV spectral region is required in many a laboratory and space applications. Films of various materials such as, for example, aluminum with thickness of **1000-4000 Å**, are widely used for this purpose. Development of a filter with a transmission cutoff positioned at the desired wavelength remains yet an unresolved and challenging problem. A novel and still fledgling approach can lead to the development of a new type of filter. The basic physical idea is very simple. Let us consider a film with a hole - straight cylindrical channel (fig.1a). If the channel diameter, $\mathbf{D_0}$, is much larger than the wavelength, λ , of incoming photons, then the photons freely pass through the hole in the film. However, if λ is larger or comparable to $\mathbf{D_0}$, then only a fraction of the incoming photons would pass through the hole. This fraction could be made very small by the proper selection of channel diameter and length. Wavelength dependent photon transmission of holes is a basis for a novel kind of filters that were called either diffraction filters (DF) or nuclear track filters (NTF) after a technology of their manufacturing. Such filters allow photons to pass with short (as compared to $\mathbf{D_0}$) wavelengths and block photons with $\lambda > \mathbf{D_0}$. Further, the notions of short and long wavelengths will be used in the same sense, i.e. as compared to channel diameter $\mathbf{D_0}$.

Actually, the idea of diffraction filtering is not new and it has been implemented in the micron wavelength region. For example, the reflection of radiation by porous structures with pore diameters in the micron range is utilized in "superinsulator" shields for thermal protection in high-vacuum low-temperature applications. Films perforated by channels with much smaller diameter, in the range **100-1000 Å**, are required for filtering the EUV radiation.

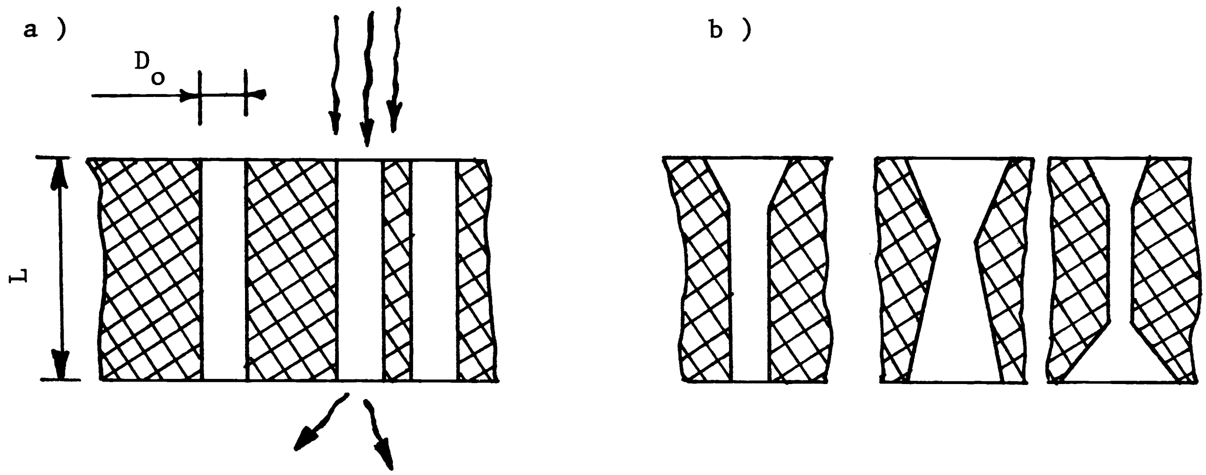

Fig.1. Films perforated by channels to filter the UV/EUV radiation.
a) straight parallel channels;
b) complex structure (funneled) channels.

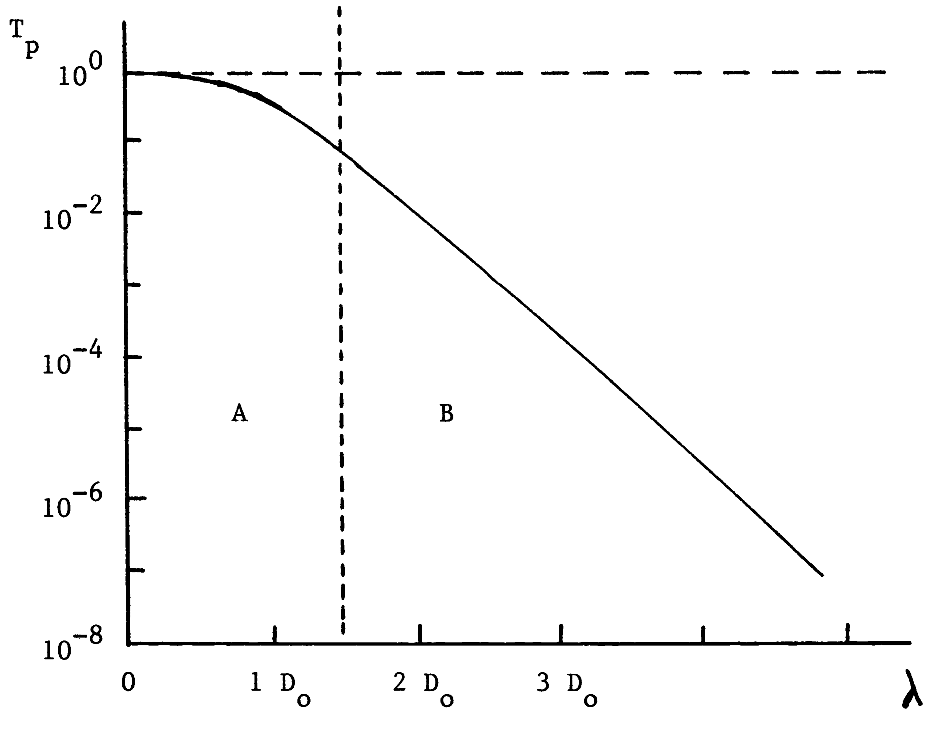

Fig.2. Schematic representation of the single pore transmission, $\mathbf{T_p}$, as a function of photon wavelength, λ. **A** and **B** are regions corresponding to small and large wavelengths.

Historically the development of NTFs for the EUV spectral region was initiated independently by two groups in Moscow in the beginning of the 1980s. For the first group, the rationale was a development of filters for soft X-ray and EUV astronomy.[1] For the second group, the goal was a development of a structure that passes fluxes of energetic neutral atoms (ENAs) but blocks the UV/EUV radiation (mostly in **1216 Å** line) presenting the major obstacle to measure neutral atoms in space plasmas.[2,3] Planetary magnetosphere imaging in ENA fluxes as well as study of solar EUV radiation are immediate candidates for NTF application in space research. Most of the development was so far done by Dr. Alexander Mitrofanov and his colleagues from the first group where the EUV filtering by NTF has been successfully demonstrated.[1,4] For practical applications, however, a further extensive study is needed to understand physical processes involved in filtering of radiation and to optimize design and technology of filter manufacturing. The present state of the technique can not be considered as mature. The aim of this article is to outline what has been done and to attract attention to the existing opportunity to develop a novel way of filtering the EUV radiation.

2. MANUFACTURING OF NUCLEAR TRACK FILTERS

The typical process of preparing NTFs consists of several steps.[5-7] First, a thin (**1-20 μm**) filter film is bombarded by heavy (**>100 u**) energetic (**>2 MeV/u**) ions. Filters can be produced, for example, from mica and various plastic materials such as Lavsan or Makrofol. The passage of a heavy ion forms a channel of intense radiation damage: molecules of the bombarded material are split into radicals. The damage can be further enhanced by exposure to UV radiation. The radicals capture oxygen and form acids which subsequently are converted, by etching, into easily soluble salts. After washing the salts out, there are openings - channels in the film where heavy ions penetrated the material. Undamaged film material can also be etched by the solutions used in the fabrication process. The shape of the etched channels depends on the ratio of etching rates, **R** , of damaged/undamaged material which in turn depends on the material of the filter, details of ion bombardment and subsequent UV treatment, type and temperature of the chemical solutions used. The value of **R** can be as high as **10^4**, which allows one to produce NTF with almost perfectly cylindrical pores with diameters in the range between **40 Å** and **10 μm**. If etching rates of damaged and undamaged material are comparable then conically shaped pores would be produced. Combining technological steps with different values of **R**, channels with complex profiles could be obtained, e.g. funneled channels with a cone at the entrance transforming into a straight part (fig.2a).

Several sources of heavy high energy ions can be used for preparing a NTF: spontaneous fission sources, nuclear reactors, and heavy ion accelerators. The first two types of sources are characterized by the broad distribution of masses and energies of fission fragments. The diameters of etched channels are, consequently, varying and the channels are not parallel. Heavy ion accelerators can provide highly parallel beams of ions of selected mass and energy. Therefore only pores produced by accelerator ions can be made parallel and homogenous in diameter. Both features are indispensable for astrophysical applications of the NTFs to filter the EUV radiation. Most of the commercially available NTFs are produced by the use of fission fragments from nuclear reactors[6] and these filters do not consequently meet the requirements for filtering the radiation. Important filter feature is the straightness of the channels. This is assured by the proper selection of ion energy - interaction of the ion with the matter must not result in substantial scattering of the ion. The number of pores in the filter can be easily controlled by ion dose and varies from one pore per whole filter up to 10^{10} cm^{-2} and corresponding geometrical transparency up to **0.15**. The most convenient way to observe visually etched submicron channels and their structure is with the help of an electron microscope.

The unique properties of NTFs are responsible for an extraordinary diverse range of their applications: from diffusion enrichment of uranium to separation of small particles such as cancer cells in the blood to clarification and cool stabilization of wine and beer by sieving out bacteria, sediment, and yeast. Hopefully, filtering of the UV/EUV radiation in laboratory and space experiments will be added to this list.

3. FILTERING OF RADIATION

3.1. Transmission of single pore

Let us consider a NTF, i.e. a film of thickness L with pores - parallel straight channels. We will define the transmission of a single pore, T_p, as a ratio of the number of photons passing through the pore to the number of photons falling on the pore entrance. Transmission T_p is a function of photon wavelength, λ, pore diameter, D_0, pore length, i.e. film thickness, L, and properties of the film material. It depends also on the angle of photon flux incidence. Parallel flux of incoming photons may diverge widely (up to 2π solid angle) after the filter, and transmission would depend on how transmitted photons are collected or blocked by collimators. We assume here that the film itself is not transparent for incoming radiation.

Theory of light penetration through arbitrary holes has yet to be developed. The problem was considered for a number of simplified cases, such as diffraction of electromagnetic radiation by a circular hole (small compared with wavelength) in a perfectly conducting plane screen[8] and in Kirchoff approximation for $\lambda << D_0$.[9] For short wavelength photons and particles, such as ENAs and neutrons, a channel serves as a collimator and near-grazing-incidence reflection at the channel walls may result in focussing of such rays.[10] Properties of real NTFs differ substantially from those considered in the literature and accurate theoretical calculations of NTF transmission remain virtually *terra incognita*.

Qualitative dependence of single pore transmission is shown schematically in fig.2. It is convenient to divide the wavelength range into two regions, **A** and **B**. For small wavelengths ($\lambda < D_0$) in region **A**, the transmission of a single pore is obviously approaching asymptotically a value of one as λ becomes smaller. For large wavelength ($\lambda > 2\,D_0$) in region **B**, the transmission drops very steeply with the increase of λ. Qualitative "back of the envelope" estimations[11] of hole transmission give dependence

$$T_p \approx D_0^{12} / (\lambda^{10} L^2) \qquad (1)$$

for region **B**. Such a steep dependence means, for example, that a filter with channel diameters between **100-300 Å** would suppress **1216 Å** radiation by a factor **1500** stronger than **584 Å**, by a factor 9 stronger than 972.5 Å, and by a factor 5 stronger than 1026 Å. Measurements indicate an even steeper dependence[11] in region **B**, for instance, such dependence as $T_p \sim D_0^{16}$ has been reported.[1] A NTF can very effectively filter radiation at region **B**, however, the absolute value of transmission in this region is rather low. Therefore the separation of radiation in region **B** is possible in the case of bright sources only. In the region **A**, where the absolute value of transmission is much higher, the ratio of transmissions for different wavelengths does not differ in such a dramatic way rendering filtering capability less effective. There were only few measurements of the transmission in region **A**, which contains such important application parameter as transmission cutoff. The realm of problems, where NTFs can be used with the utmost efficiency, is following: to suppress radiation strongly in region **B** and to allow photons from region **A** to pass through filter. Apparently, a NTF meets this requirement for imaging planetary magnetospheres in ENA fluxes: it could block background radiation in 1216 Å line and would pass ENAs through. In another example, a NTF can protect instrument measuring solar X-ray and/or EUV radiation from the very bright 1216 Å line. Presently no experimental data are available to consider the transmission properties in a more quantitative way.

Photon flux attenuation by a single pore is governed by several processes such as diffraction on the entrance hole, attenuation during propagation of the wave through dielectric waveguide - channel, and diffraction at the exit hole. This simplified picture is much more complicated in reality and includes reflection of photons at the channel walls, reflection and transmission of the radiation at the entrance and exit holes. The latter depends on the matching of the "impedances" of the channel and space outside the film. This coupling between waveguide-channel and outside homogenous medium can be controlled by the shape (funneling) of the channel entrance and exit apertures (see e.g. fig.1b) and could substantially change the transmission of the filter at selected wavelengths. Wave propagation through the dielectric channel differs substantially from propagation through a conventional metal waveguide because of the poor conductivity of filter material and very high frequency of the electromagnetic field.

3.2. Overlapping pores

If the number of pores is not large, i.e. they do not overlap, then filter transmission, T_f, is

$$T_f(\lambda) = T_p(\lambda)\ G$$

where $G = N_p (\pi D_0^2 / 4)$ is geometrical transparency of the filter and N_p is a number of pores per filter unit area. When the source is not bright and photons are scarce, which is a typical situation for astrophysical applications, it is imperative to have **G** as large as possible. The same requirement is also mandatory for planetary magnetosphere ENA imaging applications. The value of **G** is controlled by the dose of bombarding heavy ions and etched channel diameters. One can assume that pores are distributed randomly through the filter. Two important filter parameters depend strongly on **G** : i) mechanical strength; and ii) optical transmission.

Mechanical strength depends on thickness of the filter and its material. Practical experience shows that filters remain mechanically strong when $G < 0.01$. Although, the NTFs with **G** up to **0.15** have been fabricated, filters with high geometrical transparency become fragile and a source of potential problems. Importance of the mechanical strength is exacerbated by the applications in space which require the capability to withstand severe vibrations and shocks. The partial solution of this problem is in attaching filter directly, if possible, to the detector sensitive surface. Another possibility is to strengthen NTF by attached metal mesh.

Optical transmission in region **B** can be easily affected by a few overlapping pores because of its strong dependence on wavelength. For small **G**, the number of overlapping pore pairs is $(4\,G\,N_p)$ per filter unit area and the probability to have two channel axes at the distance between **r** and **r+dr** from each other is proportional to $2\,\pi\,r\,dr$. If one assumes for a rough estimate, that transmission of such a pore pair is equal to that of the pore with diameter $1.6\,D_0$, then, using formula **(1)**, filter transmission would be

$$T_f(\lambda) = T_p(\lambda)\,G\,(1 + 4\;1.6^{12}\;G)$$

in region **B**. Hence even for such small geometrical transparency as $G = 0.9\;10^{-3}$, the filter transmission would be twice as large as it follows from **(1)**. Pore overlapping requires caution in treating the results of experimental measurements, since for larger geometrical transparencies, the measured filter transmission for long wavelengths could be determined by pore overlapping rather than by transmission of individual pores. Obviously, the effect is much less pronounced in wavelength region **A**.

3.3. Transmission measurements

Measurement of filter transmissions covering the span of ten orders of magnitude is, obviously, a non-trivial experimental task. Basically, rather bright UV/EUV source and sensitive detector are required. In practice, no detector can reliably cover more than three-four orders of magnitude of photon flux. Preliminary calibrated neutral filters, i.e. with wavelength independent transmission, should be used to perform measurements. Such filters can be prepared by the same NTF technology etching large diameter channels, $D_0 >> \lambda$. Typically channel diameters are in the range **5-10 μm** in neutral filters. In such conditions, the transmission of a neutral filter is equal to its geometrical transparency. Even for large channel diameters the effect of diffraction on channel exit is important. If the detector is situated far enough from the filter, then not only average brightness is reduced (by a factor of **G**) but also local brightness would be smaller. The latter may help to keep detector in the range of its linearity and even prevent its damage.[9] Since pores are distributed randomly, it is possible to achieve required radiation attenuation installing several neutral filters sequentially .

Diffraction of the transmitted light on the channel exit aperture should be accurately accounted for in a filter transmission measurements. For large λ, diffraction can occur at large angles up to all hemisphere. Such diffraction has been experimentally observed for various filter parameters.[12]

4. ALTERNATIVE TECHNOLOGIES

Low porosity of NTFs prompts the search of other structures with submicron channels and intrinsically higher geometrical transparency. For filters with a high geometrical transparency and submicron channel diameters, not only channel diameter but interchannel walls would be much smaller than the wavelength of radiation. The transmission of such a "fluffy" filter seems to be equal to that of the film with the same density per unit area.

4.1. Microchannel plates

Microchannel plates (MCP) with well-developed manufacturing technology are obvious candidates to develop novel filtering structures. The geometrical transparency of commercially available MCPs is between **0.5** and **0.6**, and channel diameters are as small as **4μm**. MCP technology allows also manufacturing of funneled channels. Even rectangular channels could be produced with overall MCP geometrical transparency up to **0.9**.[13] Making MCPs with smaller channel diameters faces technological difficulties, particularly the inhomogeneity of channel diameters is increasing. The latter is important for MCP application for electron multiplication but is less critical for radiation filtering. The reasonable guess is that, with technology at hand, it would be feasible to reduce channel diameters down to **1 μm** while maintaining high geometrical transparency. The important feature is the possibility to control within certain limits the conductivity of microchannel walls and influencing herewith the wave propagation through a waveguide-channel. A decrease in microchannel diameter will result in a decrease of MCP thickness, if the same channel length-to-diameter ratio or collimator field-of-view (say **1°**) is to be maintained. Hence a MCP with **1 μm** channels would be only **50 μm** thick with inherent problem of mechanical fragility as a consequence. Another possibility is to decrease the microchannel entrance and/or exit diameters in existing MCPs by increasing the thickness of the metal layer which is usually deposited on MCP surfaces. Channel diameters would remain the same in the their middle part but would be reduced down to a fraction of a micron at the entrance/exit. Geometrical transparency of such MCP would also be reduced down to a few per cent.

As it has already been mentioned, the thickness of walls between channels also would become smaller than the photon wavelength which could affect wave propagation. Neighbor channels may even become coupled rendering consideration of radiation filtering by an array of individual channels irrelevant. MCP presents a highly, almost perfectly ordered structure and one should expect very strong interference effects. This feature of MCP is well known to everybody who illuminated MCP by a laser beam and observed wonderful interference structure on, say, a laboratory wall or ceiling. Therefore filtering of radiation by MCP-like structures would strongly depend on angle of photon incidence as well as angle at which the transmitted radiation is collected.

4.2. Anodically oxidized aluminum membranes

Formation of porous anodic films on aluminum is a well-developed technology[14,15] which may provide an efficient way of preparation ordered submicron structures with high geometrical transparency. When aluminum is anodized in suitable electrolyte, a porous oxide layer develops on the surface. This film consists of the close-packed hexagonal array of cells, each containing a cylindrical pore. The pore size and pore density depends on anodizing voltage (typical range **10-200 V**), whereas thickness of the porous layer is controlled coulombically. Pores are essentially parallel and pore sizes in the range **100-2500 Å**, film thickness of over **100 μm**, and geometrical transparency up to **0.25** can be achieved. Recently developed technology allows detachment of the porous films by a programmed anodizing voltage reduction sequence.[15,16] It is possible now not only to separate porous film from the bulk aluminum but the interface region of this film containing irregular pores could be etched off.[15,16] Such porous films may become convenient and useful filters in the UV/EUV spectral range. Anodic membranes are commercially available from *Anotec Separation Ltd (UK)*.

4.3. Transmission gratings

Novel free-standing transmission gratings are finding more and more applications in EUV, X-ray, and matter-wave diffraction and spectroscopy.[17] Primarily the requirements of the AXAF X-ray telescope fueled developments in this area. The gratings are manufactured by a complex sequence of sophisticated technological steps including holographic and X-ray lithographies, reactive-ion etching, electroplatings, and gold liftoffs. The grating consists of a set of parallel gold bars with the period down to **1000 Å** and geometrical transparency approximately one half. The grating can be supported by a fine metal mesh. A typical grating has a period of **2000 Å** and is **1 μm** thick, i.e. ratio of channel "depth" to the distance between bars is equal to ten.[17] Hence, such grating serves as a **5°** collimator in one dimension.

Obviously, transmission gratings can be used for filtering EUV radiation. For example, two sequentially installed and perpendicularly oriented gratings could provide an efficient filter against **1216 Å** background for planetary magnetosphere ENA imaging. Transmission of a single grating should be highly sensitive to polarization of the photons making it possible to build efficient polarimeters for the EUV spectral region. Different types of transmission gratings are commercially available form *X-Opt Inc. (USA)* and *Heideman, GmbH (Germany)*.

4.4. "Drilling" channels

Small holes in metal sheets could be produced by a laser light. Obviously, diameters of channels can not be made less than the light wavelength and it is difficult, if not outright impossible, to produce a channel with the length much larger than its diameter. Ion drilling may have a better potential. Ion beams can be focussed down to submicron sizes and material sputtering can be rather efficient. However, again it would be difficult to drill long channels. Such ion drilling must be a highly automated process with extremely accurate and stable beam positioning. However, the enormous number of holes to be drilled and a limit on ion current to prevent melting of film material may render this approach also unpractical.

5. FUTURE DEVELOPMENTS

The basic physics of light transmission by submicron structures is presently poorly understood and requires combined research effort by both theoreticians and experimentalists. Special interest may present the effect of the form of channel entrance (funnel) on pore transmission at ceratin wavelengths. Another new possible development is connected with the polarization of the light. For example, highly anisotropic plastic film may show different etching rates in different directions along its surface. In that case, elliptical holes would be etched in the NTF. Transmission of such holes would depend, obviously, on polarization of the light. Development of such elliptical pore

NTFs as well as properties of transmission gratings may lead to a new generation of efficient polarizers for the UV/EUV spectral region.

Use of submicron structures presents a novel, fledgling approach to the filtering of the UV/EUV radiation. Various techniques are used to produce submicron pores and diffraction based filters are characterized by many unique properties. These novel filters should find applications in a variety of laboratory and space experiments.

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