R009-P20
ポスター４：11/26　AM1/AM2（9:00-12:00）

金属合金を用いた多層膜反射鏡の開発

#吉川 一朗[1)], 桑原 正輝[2)], 吉岡 和夫[3,4)], 村上 豪[5)], 鈴木 雄大[6)]
([1)] 東大, ([2)]Rikkyo Univ., ([3)] 東大・新領域, ([4)] 東大・新領域, ([5)]ISAS/JAXA, ([6)]JAXA/ISAS

Development of Multilayer Mirrors Using Metak Alloys

#Yoshikawa Ichiro[1)], Masaki Kuwabara[2)], Kazuo Yoshioka[3,4)], Go Murakami[5)], Yudai Suzuki[6)]
([1)]University of Tokyo, ([2)]Rikkyo University, ([3)]Department of Complexity Science and Engineering, The University of Tokyo,, ([4)]Department of Complexity Science and Engineering, The University of Tokyo,, ([5)]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, ([6)]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

At the beginning of the 21st century, imaging of the Earth's inner magnetosphere using extreme ultraviolet light (EUV) became possible, bringing significant achievements to the field of geophysics. A multilayer mirror that efficiently collects the resonance scattering line of singly ionized helium (wavelength 30.4 nm) played a key role in this success. By stacking 20 layers of molybdenum (Mo) and silicon (Si) on the mirror surface, the reflection rate, which would normally be less than a few percent, was increased to 20%, leading to the success of the "Nozomi" satellite's inner magnetosphere imaging. The "Kaguya" satellite carried out an ambitious attempt to provide a comprehensive view of the Earth's magnetosphere from lunar orbit, where Mo/Si multilayer mirrors also contributed to new achievements.

The Mo/Si multilayer mirrors possess numerous advantages, such as high resistance to environmental changes like temperature, humidity, and pressure, and can sometimes be cleaned if contaminated. For this reason, they are also utilized in the field of extreme ultraviolet lithography (EUVL), which uses a 13.5 nm wavelength as a light source.

As EUV imaging became recognized as one of the observational methods in the field of earth and planetary sciences, a team combining science and engineering was recently formed at the University of Tokyo, which developed the ultra-small (6U) satellite "EQUULEUS." To mount an EUV imager on a 6U-sized satellite, it was necessary to reduce the mirror surface area to about half of the conventional size, which required improving the multilayer reflectivity by at least twofold. At that time, the project leader focused on the fact that multilayer mirrors composed of magnesium (Mg) and silicon carbide (SiC) (and also B4C and Mg) exhibited high reflectivity, aiming to miniaturize the imager.

The reflectivity of the Mg/SiC multilayer mirror that was manufactured reached over twice that of the Mo/Si multilayer mirror (about 50%) in laboratory calibration experiments, but it was discovered that exposing the mirror to slightly high humidity (˜65%) or high temperature (˜55° C) for a short period led to the formation of spots, as shown in Figure 2, resulting in a decline in reflectivity. It was identified that these spots did not occur on the surface of the multilayer mirror, but rather at the interfaces between the layers, where Mg was found to diffuse into the SiC layer, causing interfacial degradation. However, no decisive solution to this problem has been found.

Because Mg and Al have low absorption (k) and high refractive index in the EUV wavelength region (making them optimal as one part of a multilayer pair), researchers in space science worldwide, as well as in the EUV lithography field (EUVL), have attempted to use them in multilayer mirrors. However, through joint research with industrial researchers in the EUVL field, it was found that Mg and Al exhibit significant diffusion at the interfaces, making it difficult to create stable interfaces. It seems that researchers around the world share this understanding.

In this study, we present experimental results on the use of Mg and Al alloys, which cannot form stable interfaces as single elements, as materials for multilayer mirrors.

２１世紀の初頭、極端紫外光（ＥＵＶ）を用いた地球内部磁気圏の撮像が可能となり、ヘリウム一価イオンの共鳴散乱線（波長 30.4nm）を効率よく集光する多層膜反射鏡が、地球物理学の分野に大きな成果をもたらした。Ｍｏ（モリブデン）とＳｉ（シリコン）を２０層、鏡の表面に積層することにより通常では数%にも満たない鏡の反射率が２０%にまで向上し、「のぞみ」衛星の内部磁気圏撮像を成功に導いた。「かぐや」衛星では月の周回から地球磁気圏を一望するという野心的な試みを遂行し、ここでもＭｏ/Ｓｉの多層膜反射鏡が新しい成果の創出に貢献した。Ｍｏ/Ｓｉ多層膜は、温度、湿度や圧力などの環境変化に対する耐力が高く、汚染しても洗浄できる場合がある等の利点が多い。そのため、１３．５ nm を光源とする極端紫外光リソグラフィ（ＥＵＶＬ）分野でも利用されている。
地球惑星科学分野における観測手段の一つとしてＥＵＶによる撮像が認知されるに至り、最近、東京大学内で理工一体チームを編成し、超小型（６Ｕ）衛星エクレウスを開発した。６Ｕサイズの衛星にＥＵＶ撮像機を搭載するには従来の反射鏡面積を約半分に縮小する必要があり、それを補うために多層膜の反射率を最低でも２倍程度にまで向上させる必要が

ある。当時、研究代表者は、Mg と SiC（並びに B4C と Mg）からなる多層膜が高い反射率を持つ事に注目し、撮像機の小型化を図った。

製造した Mg/SiC 多層膜鏡の反射率は、室内校正実験ではＭｏ／Ｓｉ多層膜の２倍以上の反射率（５０％程度）を製造直後には達成していたが、やや高い湿度（～６５％）や高温（～５５℃）に短時間曝すだけで、図２に示す斑点が多層膜反射鏡に発生し、反射率が低下することが解ってきた。これらの斑点は多層膜の表面に発生したのではなく、多層膜の層の界面においてＭｇがＳｉＣ層に拡散し、界面を犯していることが原因であるところまでは突き止めたが、決定的な改善策は見つかっていない。

ＭｇとＡｌはＥＵＶ波長領域においてｋが小さく（吸収が小さい)、屈折率が大きい（多層膜のペアの一方としては最適である）事から、これまでにも世界各国の宇宙科学研究者のみならず、極端紫外光露光リソグラフィ分野（ＥＵＶＬ）が、多層膜反射鏡への利用を試みてきた。様々な材料の組み合わせを極端紫外光露光リソグラフィ分野（ＥＵＶＬ）の民間企業の研究者と検討したが、Ｍｇ、Ａｌは界面での拡散が大きく、安定した界面ができないことが分かってきた。世界の研究者もそのように理解しているようである。

本研究では、単体では安定な界面を生成できない Mg や Al を合金として用いた場合の実験結果について紹介する。