	かなもり よしあき
氏名	金森 義明
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指導教官	東北大学教授 羽根 一博
論文審査委員	主査 東北大学教授 羽根 一博 東北大学教授 清野 慧 東北大学教授 江刺 正喜 東北大学助教授 湯上 浩雄

論文内容要旨

Chapter 1 Introduction

This dissertation is concerned with the subwavelength gratings (SWGs) for reflection control in visible and near-infrared wavelengths. The antireflection SWGs will be powerful when fabricated on transparent material such a glass material, and on semiconductor material for optical sensor and light emitting diode (LED). Major problems in the antireflection SWGs are described as follows. The antireflection properties are improved by decreasing the grating period and increasing the grating depth. However, up to now, the aspect ratio of 0.63 is the highest value in the two dimensional SWGs etched directly. It is difficult to fabricate the optimum grating shape with high aspect ratio in large area with low cost using conventional fabrication techniques. There are no guidelines to design two-dimensional antireflection SWG with the complex dielectric constant. There is no experimental report on the application to the LED and its light emitting properties. The purposes of this study are to analyze and solve the above problems. The fabrication techniques that are developed by this work can be applicable to the fabrication of the near-field optics and photonic crystal optics that are promised as the next generation optical technology. Thus, the developed techniques are valuable in these fields.

Chapter 2 Rigorous Coupled-Wave Analysis and general characteristic of antireflection SWGs

The Rigorous Coupled-Wave Analysis (RCWA) for the two dimensional SWGs with the taper

sectional shape and the complex dielectric constant was formulated. The RCWA program made up was used to analyze the antireflection SWGs fabricated in this work. The optical properties of the antireflection SWGs were analyzed. The guidelines to design the antireflection SWGs consisting of silicon were shown. Differences of the optical characteristics of the tapered SWGs among the dielectric substance, imperfect conductor and perfect conductor were shown. From these calculations, it has been found that the grating period and the aspect ratio are the important parameters to design the antireflection SWGs.

Chapter 3 Broadband antireflection SWGs for silicon and glass substrates fabricated by electron beam patterning and fast atom beam etching

It has been shown that fast atom beam (FAB) etching combined with electron beam (EB) patterning is useful for the fabrication of SWGs with a 100 nm order period grating on silicon and glass substrates.

For silicon SWG, the smooth tapered grating with the high aspect ratio was fabricated on the silicon surface as shown in Fig. 1. Figure 2 shows the reflectivity of the SWG fabricated as a function of the wavelength. At the wavelength of 400 nm, the reflectivity was decreased to 0.5% from 54.7% of silicon substrate. The fabricated antireflection silicon surface will be useful for preventing the reflection at the surfaces of solar cells and electro-optical devices. The theoretical calculation was also carried out on the basis of RCWA. The reflectivities calculated for a model with seven-layered square subwavelength grating could explain the measured reflectivities well.

For glass SWG, the smooth tapered grating was fabricated on the glass surface. To my knowledge, the fabricated SWG had the shortest grating period among two-dimensional antireflection SWGs fabricated on glass substrates. At wavelengths from 400 nm to 800 nm, which included the visible region, the reflectivity of the

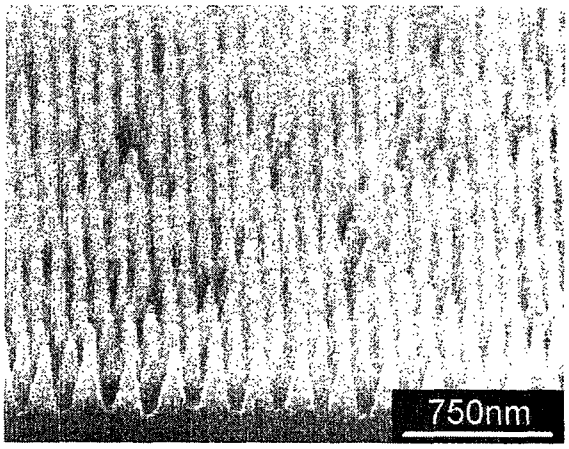

Fig. 1: Scanning electron micrographs of the SWG fabricated on the silicon substrate. The grating period is 150 nm, and the groove is 350 nm deep.

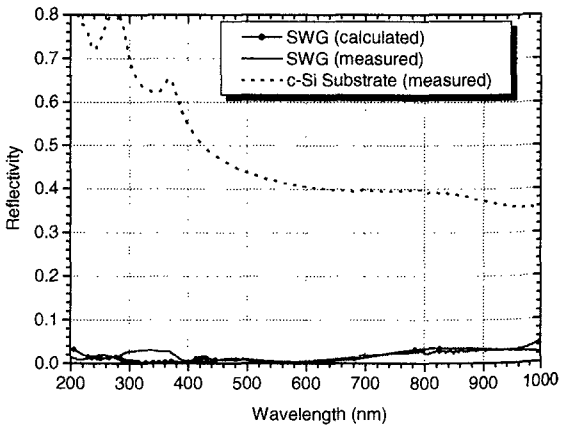

Fig. 2: Reflectivity as a function of the wavelength.

SWG was lower than 1% while that of the glass substrate was higher than 5%. The theoretical calculation was also carried out on the basis of RCWA. The reflectivities calculated for a model with six-layered square subwavelength grating could explain the measured reflectivities well.

Chapter 4 Broadband antireflection SWGs for silicon substrates fabricated using 100-nm period porous alumina membrane mask

I have shown that the porous alumina membrane is useful as a mask for the fabrication of deep SWG with the FAB etching. 100 nm period gratings with aspect ratio higher than 6 were generated on silicon substrate as shown in Fig. 3. At the wavelengths from 370 nm to 800 nm, the reflectivity of the SWG decreased to be lower than 1.6 % from around 40 % of polished silicon surface. The theoretical calculation based on the RCWA explained the measured reflectivities well. Since the porous alumina membrane is easily widened, the proposed process will be useful for the fabrication of antireflection SWGs in a large area on silicon substrate.

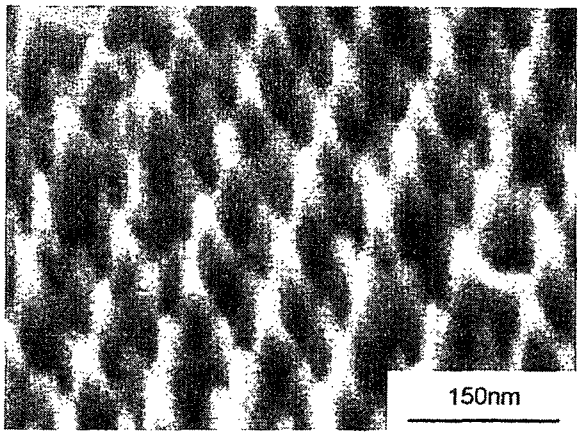

Fig. 3: Scanning electron micrographs of the column type SWG.

Chapter 5 Broadband antireflection SWGs for polymethyl methacrylate fabricated with molding technique

It has been shown that molding technique is useful for the fabrication of SWG with a 200 nm period grating on polymethyl methacrylate (PMMA) film. The PMMA SWG having reverse shape grating of the mold SWG was replicated well. The PMMA SWG decreased the reflection at wavelengths from 400 nm to 800 nm. At the wavelengths, the reflectivity decreased to approximately half of that of the PMMA film. In the SWG region, the scattering of the transmission light was not observed, and the reflected light from the surface of PMMA film decreased in comparison with the other region. The proposed process will be useful for the fabrication of antireflection SWGs in a large area with low cost.

Chapter 6 Broadband antireflection SWGs for light emitting diodes and photo diodes fabricated on GaAlAs surfaces

It has been shown that FAB etching combined with EB patterning is useful for the fabrication

of SWG with a 200 nm period grating on GaAlAs double power double hetero (DDH) junction structure. The GaAlAs DDH structure functions as photo diode (PD) and LED. The novel etching technique using the two kinds of process gas of the FAB for fabricating the tapered grating on GaAlAs surface was proposed. The smooth tapered grating with the high aspect ratio was fabricated. At wavelengths from 400 nm to 780 nm, the reflectivity was decreased to 1.0%. Under the laser diode (LD) light illumination, the open-circuit voltage, short-circuit current and total conversion efficiency were improved by fabricating the SWG. From the observation of the light emission by CCD, it was confirmed that the emission was increased in the SWG area, even over the angle of total internal reflection.

Chapter 7 Summary

The conclusions of this dissertation are given.

審査結果の要旨

一般に屈折光学素子の表面におけるフレネル反射を低減することは、光学システムの性能を向上するために、欠かせない。著者は入射波長よりも小さな周期を持つサブ波長格子を素子表面に製作することで、可視から近赤外の広い波長領域において、フレネル反射を低減することに成功した。厳密な電磁界解析により現象を解析し、設計の指針を明らかにすると共に、応用においては、光センサや発光ダイオードの効率を改善した。本論文は、この研究成果についてまとめたもので、全文7章よりなる。

第1章は序論であり、本研究の背景と目的を述べている。

第2章では、厳密解法の電磁界解析プログラムを作成し、サブ波長格子を理論的に解析した結果について述べている。格子周期とアスペクト比が反射特性に大きく影響することを明らかにしたことは、格子設計の指針を得る上で重要な知見である。

第3章では、電子線描画と高速原子線加工によるサブ波長格子の製作方法を提案し、製作と評価を行った結果について記述している。これまでにない高いアスペクト比と滑らかなテーパー形状を実現し、可視波長帯域で優れた反射防止特性が得られたことは、有用な成果である。

第4章では、陽極酸化ポーラスアルミナをマスクとして高速原子線加工を行い、周期100nmでアスペクト比6以上のサブ波長格子をシリコン基板に製作した結果について述べている。370nmから800nmの波長帯域において、優れた反射防止特性が得られた。これはサブ波長格子の製作方法に関する新しい提案であり、多くの材質に対して大面積で製作できる可能性を示したことは実用上、重要な結果である。

第5章では、鋳型転写技術を用いてポリマー材料へサブ波長格子を転写した結果について述べている。鋳型の格子が10nm領域で転写できること示したことは、低コストで大面積に格子を製作できる可能性を示しており、重要な成果である。

第6章では、電子線描画と高速原子線加工により、ガリウム砒素発光ダイオード表面にサブ波長格子を製作した結果について記述している。ガリウム砒素のエッチング特性を利用し、テーパー形状でアスペクト比の高い格子を製作し、高放射率の発光ダイオードを実現した意義は、実用上大きい。

第7章は結論である。

以上要するに本論文は、可視から近赤外の広い波長領域においてフレネル反射を低減するために、サブ波長格子を提案し、極微細なリソグラフィ加工により、これまでにない無反射表面の実現に成功したものであり、光工学および精密加工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。