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Metamaterials formed on the surface of silicon carbide by plasma treatment

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Abstract. In the presented work, a unit cell of a self-complementary metamaterial was designed, which is alternating patches and holes in a conductive graphene-like layer 7 μm thick on a silicon carbide substrate 250 μm thick. The results of a numerical study of the developed structure are presented. The calculations considered the conductivity of the graphene-like film, as well as the dielectric parameters of the silicon carbide substrate. The developed metamaterial is designed to convert circular polarization into linear; the central operating frequency of the resulting structure is 10 GHz. The dimensions of the unit cell are 2.8 mm × 5.6 mm. The elements obtained can be used in microwave technology and antenna structures. For the manufacture of structures, it is planned to use the method of plasma-chemical etching of silicon carbide in a fluorine-containing gas environment, which destroys the silicon component and leaves a graphene-like conductive layer on the surface. The thickness of the graphene-like layer depends on the power of the inductively coupled plasma source and the processing time; in this work, a thickness of 7 μm was taken, obtained at 800 W and 8.5 minutes of etching SiC in an SF_6/Ar atmosphere.

Keywords: plasma etching, metamaterials, graphene-like film, silicon carbide, microelectronics

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Формирование метаматериалов на поверхности карбида кремния методом плазменной обработки

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Аннотация. В представленной работе была спроектирована элементарная ячейка самодополняющего метаматериала, представляющего собой чередующиеся патчи и отверстия в проводящем графеноподобном слое толщиной 7 мкм на подложке из карбида кремния толщиной 250 мкм. Представлены результаты численного исследования разработанной структуры. При проведении расчетов учитывались проводимость графеноподобной пленки, а также диэлектрические параметры подложки из карбида кремния. Разработанный метаматериал предназначен для конвертации круговой поляризации в линейную, центральная рабочая частота полученной структуры 10 ГГц. Размеры элементарной ячейки 2.8 мм × 5.6 мм. Полученные элементы могут быть использованы в СВЧ-технике и антенных структурах. Для изготовления структур планируется применять метод плазмохимического травления карбида кремния в среде фторсодержащего газа, при котором происходит деструкция кремниевой составляющей и на поверхности остается графеноподобный проводящий слой. Толщина графеноподобного слоя зависит от мощности источника индуктивно-связанной плазмы и времени обработки, так в работе была взята толщина 7 мкм, получаемая при 800 Вт и 8,5 минутах травления SiC в атмосфере SF_6/Ar.

Ключевые слова: плазменное травление, метаматериалы, графеноподобные пленки, карбид кремния, микроэлектроника

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Introduction

Modern technologies of micro- and nanoelectronics, operating in extreme conditions such as high temperatures, aggressive environments, strong electric fields, require materials with a unique combination of mechanical strength, thermal stability and controlled electrophysical properties. Silicon carbide (SiC) is a promising basis for such devices due to its wide band gap, high thermal conductivity and chemical inertness. However, to create functional elements such as metamaterials with specified electromagnetic characteristics, it is necessary to form conductive nanostructures on the SiC surface, in particular graphene-like films [1]. One of the most effective methods for their production is plasma etching, which allows for controlled modification of the SiC surface with the formation of conductive carbon layers with atomic precision. The formation of graphene-like films on SiC using plasma etching offers a fundamental new solution that combines the advantages of a semiconductor substrate and a conductive carbon layer [2].

Metamaterials [3] are artificially engineered thin and tightly packed two-dimensional arrays of resonant structures designed to have properties that are not found in naturally occurring materials. They achieve these unusual properties through their carefully structured internal architecture rather than their chemical composition. Metamaterials have been employed to control and manipulate electromagnetic waves.

A specific class of metamaterials exhibits band-pass filtering properties for one linear polarization while simultaneously acting as a band-stop filter for the orthogonal linear polarization [4]. An application of such structures could be the conversion of incident circularly polarized waves to linearly polarized waves. One such metamaterial is a self-complementary patch and hole metasurface [4].

In this paper the feasibility of fabricating self-complementary metasurfaces on a SiC substrates using a two-stage plasma chemical etching method is studied.

Materials and Methods

In this work, we propose obtaining a conductive layer on the surface of silicon carbide by a two-stage plasma-chemical etching method. In this method of obtaining, at the first stage, the near-surface layers are removed in a fluoride and oxygen plasma environment at minimum bias voltage values and maximum voltage values of the inductively coupled plasma source. This mode allows for the actual plasma polishing of the surface and the removal of several defective surface layers. At the second stage, the bulk of the material was etched in fluoride plasma, which made it possible to remove the silicon component from the surface layers with the formation of a conductive graphene-like layer.

To study the possibility of creating self-complementary metasurfaces on SiC substrates by a two-stage plasma-chemical etching method, a cell of a rectangular patch-hole metasurface was designed and numerically studied using the Ansys HFSS full-wave electromagnetic simulation software.

The designed unit-cell is shown on a Fig. 1. The unit-cell consists of a 250 μm thick SiC substrate (colored light grey) and an etched 7 μm conductive graphene-like layer (colored dark grey on a Fig. 1). The relative permittivity of a SiC substrate in a simulation is equal to 10 and $tg(\delta) = 1\times10^{-6}$. Periodic boundary conditions are applied to the *A*, *A'*, *B*, *B'* sides of the unit-cell. Two ports are placed at the sides parallel to the SiC surface. The dimensions of the designed structure are 2.8 mm by 5.6 mm.

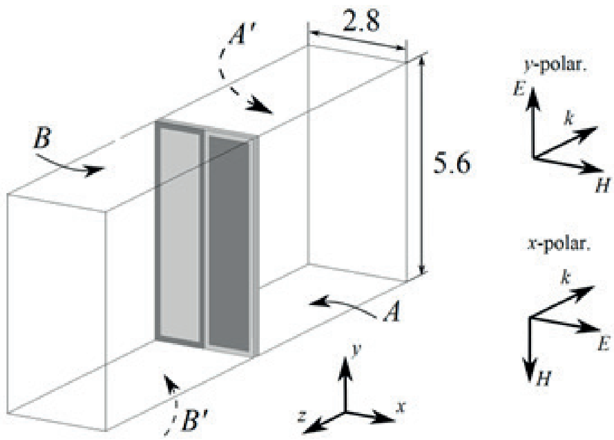

Fig. 1. Unit-cell of the rectangular patch and hole metasurface etched on a SiC substrate. Periodic boundary conditions are applied to the sides *A*, *A'*, *B*, *B'*

Results and Discussion

Simulated transmission and reflection coefficients of the designed unit-cell at normal incidence are shown on a Fig. 2.

The magnitudes of the transmission coefficients for *y*-polarized and *x*-polarized waves are shown in Fig. 2, *a*. The central operating frequency of this metamaterial is 10 GHz. At that frequency, the designed metasurface functions as a band-pass filter for the *y*-polarized wave, and simultaneously as a band-stop filter for the *x*-polarized wave. The reflection coefficient for the *y*-polarized wave in Fig. 2, *b* approaches zero, confirming the performance of the metasurface.

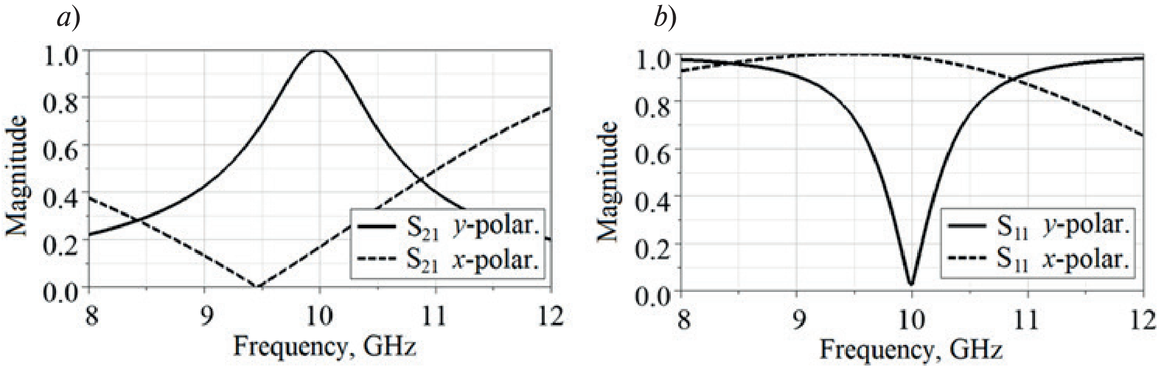

Fig. 2. Simulated magnitude of a transmission (*a*) and reflection (*b*) coefficients at normal incidence for rectangular patch and hole metamaterial unit-cell

The numerical study conducted demonstrates the potential for fabricating self-complementary metasurfaces on SiC substrates, for polarization conversion. However, experimental study is planned to validate the proposed hypotheses.

Conclusion

A unit cell of a self-complementary metamaterial for converting circular polarization into linear polarization has been developed and numerically studied. The metamaterial consists of alternating sections and holes in a 7-μm-thick conductive graphene-like layer on a 250-μm-thick silicon carbide substrate. The central operating frequency of the developed metamaterial is 10 GHz. The numerical study demonstrates the possibility of creating self-complementary metasurfaces on SiC substrates for polarization conversion in the X-band.

The developed and numerically studied structure, like most metamaterials, is periodic, which means that it is sufficient to model only one unit cell with periodic boundary conditions on the faces. To manufacture an array of self-complementary metasurface cells, it is planned to use the method of creating a conductive graphene-like film on the SiC surface by plasma destruction of the silicon component.

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