Advanced Fabrication Method of Planar Components for Plasma Diagnostics

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(Received 4 December 2006 / Accepted 11 March 2007)

As the importance of plasma imaging diagnostics increases, the fabrication of high performance millimeter-wave planar components becomes essential. This paper describes the development of high performance millimeter-wave planar components such as antennas and filters using a low-loss fluorine substrate. The problems to be solved are the low degree of adhesion between copper foil and the fluorine substrate and the shape of the antenna pattern. In order to solve the problems, surface treatment of fluorine films and a fabrication method using Electro Fine Forming (EF2) are utilized.

Keywords: plasma diagnostic, millimeter wave, graft polymerization, electron beam, surface treatment, peel strength, dielectric constant, adhesion, PTFE, planar antenna

DOI: 10.1585/pfr.2.S1042

1. Introduction

Millimeter-wave imaging diagnostics such as phase imaging interferometry (PII), microwave imaging reflectometry (MIR), and electron cyclotron emission imaging (ECEI) have proven to be useful in obtaining 2-D pictures of electron density, electron temperature, and their fluctuations [1–3]. They are powerful tools to study localized magnetohydrodynamic (MHD) instabilities and micro instabilities, which are considered to be responsible for the anomalous transport of magnetically-confined plasmas. Microwave imaging systems are now installed in the large helical device (LHD) and the Tokamak EXperiment for Technology Oriented Research (TEXTOR) [4, 5].

As the importance of millimeter-wave imaging diagnostics increases, the fabrication of high performance millimeter-wave planar components such as high-frequency planar antennas and filters becomes essential [6]. One of the methods is to use fluorine resin as an antenna substrate. If the planar antennas are used as transmitting or receiving antennas, one can easily control the beam direction of the antennas and decrease the height of the antenna in comparison with that of the horn antenna.

The use of low-loss fluorine substrate is essential to obtain low cost, high performance millimeter-wave planar components. However, there are two problems to be solved, the low degree of adhesion between the copper foil and the fluorine substrate and the edge shape of the pattern.

For the first problem, there have been several studies on improving the surface properties of fluorine resin using various surface modification methods [7–12]. Along with wet chemical treatment, plasma and ion beam treatments have been considered as efficient surface modification techniques. It has also been reported [12] that the adhesion between the fluorine resin and metal can be substantially improved by graft copolymerization with certain functional monomers. However, the method requires many processes, and the dielectric constant after the treatment was not investigated.

We have proposed several methods to solve these problems. One solution is a surface treatment of the fluorine substrate to increase the peel strength of the copper foil. The other is a fabrication method using Electro Fine Forming (EF2) technology that produces excellent patterns without side edges.

We report on the results of the surface treatment of fluorine films by radiation-induced graft polymerization to improve the adhesion and the measurement of the dielectric constant before and after the treatment. Antenna fabrication using EF2 technology is also introduced. The millimeter-wave antenna's observed characteristics are described and compared with the simulation.

2. Experimental Apparatus and Method

2.1 Surface treatment by radiation-induced graft polymerization

PTFE films with 0.3 mm thickness (Yodogawa Hu-Tech) were used in this experiment. An acrylic acid (AAc) monomer (Kanto Chemical) was used for the graft poly-

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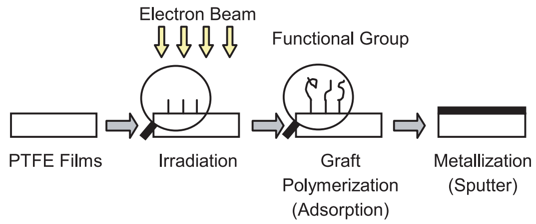

Fig. 1 Processes of surface treatment, graft polymerization, adsorption and metallization.

merization.

The processes of the surface treatment, graft polymerization, adsorption, and metallization are shown schematically in Fig. 1. The pre-irradiation method was used as a grafting technique. The films were irradiated in a nitrogen atmosphere by an electron beam at Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency. The irradiation was carried out at a dose ranging from 10 to 20 kGy, and the films were maintained at about −78°C. When the fluorine binding was cut by the electron beam, radicals were generated at cut points in the PTFE films. After the grafting reactions were performed at a temperature of 50°C, the carboxyl group of AAc, a hydrophilic group with good compatibility with metal, was introduced onto the surface of the PTFE. Different degrees of grafting were achieved by immersing the films for different intervals, from 0.5 to 3.5 h, in the monomer solution. The acrylic acid was used as a monomer, and the concentration of the monomer was from 10 to 50 %. Water was used as a solvent. After the graft polymerization, the PTFE films were washed thoroughly with methanol to remove the unreacted monomer and homopolymer. After that, the acrylic-acid-grafted films were dried under reduced pressure at about 30°C for about 15 h until a constant weight was reached. The degree of grafting is calculated as follows:

$$\text{degree of grafting [\%]} = (W_g - W_0)/W_0 \times 100, \quad (1)$$

where W_0 is the initial weight of the film and W_g is the grafted weight of the film.

After the graft polymerization, the copper was adsorbed onto some of the PTFE films. After each of the surface treatments described above, chrome (thickness $t = 0.05\,\mu\text{m}$) and copper ($t = 0.3\,\mu\text{m}$) were sputtered onto the surface of the films, and then the copper was electrolytically plated to a thickness of 20-30 μm. Sputtering was carried out using an STH10311 sputtering system (Sinko Seiki).

2.2 Peel testing and electric property

The adhesion between the copper and the grafted films was measured using a 90° peel testing system, in which the peeling rate of the metal strips was kept constant at 50 mm/min.

The dielectric constant of the films before and after the treatment was measured by a cavity resonance method.

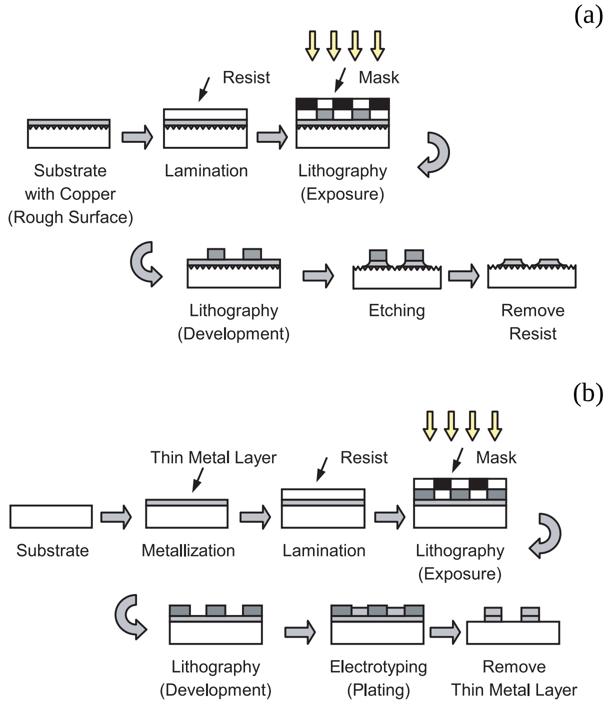

Fig. 2 Etching fabrication processes (a) and EF2 fabrication processes (b).

2.3 EF2 fabrication technique

The processes of conventional fabrication technique (etching) are shown schematically in Fig. 2 (a). When we use this etching technique, there are a few problems. First is the shape of circuit pattern such as the side edge. Due to the side edge, the resonance frequency of an antenna is often shifted away from the calculated frequency. This frequency shift is serious for narrow bandwidth components such as planar patch antennas. Second is the irregularity between the substrate and the copper foil, which is carried out for the purpose of increasing the adhesion between the two. As a result, conductor loss of the transmission line increases, especially at higher frequencies. Third is the limitation of line width and gap width of the circuit pattern.

In this paper, we have proposed a method to solve the above problems. That is a fabrication method using the EF2 technique, which gives an excellent pattern. Using this technology, an ultrafine pattern can be formed. EF2 is thought to be most appropriate for the fabrication of planar components on substrates.

The processes of the EF2 fabrication technique including the lithography process, the electrotyping process is shown schematically in Fig. 2 (b). EF2 abilities are made possible by the integration of two unique technologies. One is “Parex Patterning Technology” which is a microlithography exposure technique used to enhance forming resolution and provide precise aperture patterns with micron level tolerances. Another is Maxell’s patented “Stay-

Land Technology" which controls plating thickness and ensures an evenly distributed metal deposition so that parts are formed in a very controlled and uniform manner. EF2 has five characteristics. First is an excellent vertical cross-section. Second is the formation of holes smaller than the plate thickness. Third is high-precision hole measurement below +/−5% plate thickness. Fourth is accurately controlled hardness of about Hv 500. Fifth is plate thickness control. In the case of the range from 10 μm to 300 μm, the precision is better than 8 %.

3. Experimental Results and Discussion

3.1 Peel adhesion strength

Figure 3 shows the effect of the degree of grafting on the peel strength of (Cu+Cr) / AAc (concentration = 10 %) / PTFE. The peel strength of untreated (Cu+Cr) / PTFE was 0.40 kgf/cm. Note that a considerable increase in peel adhesion strength is obtained by AAc graft polymerization on the PTFE surface, when the degree of grafting is less than 0.2 %. There are two methods of reaction. One is called the liquid phase method and the films are immersed in the liquid during the reaction. The other is called the impregnation method and the films are immersed with wrapping a cloth to ensure uniform reaction onto the surface of the films. The achieved peel adhesion strength of PTFE was 1.64 kgf/cm. The increase in adhesion strength between the metal and the grafted PTFE films may have resulted from cross-linking reactions or covalent binding between the copper ion and the carboxyl group of AAc that was introduced onto the thin surface layer of the PTFE films.

When the degree of grafting is exceeds 1 %, the peel strength is decreased. We believe that arises because the surface condition of films has changed owing to the attachment of many carboxyl groups and the stable surface structures of the films have been broken down by much reaction in AAc.

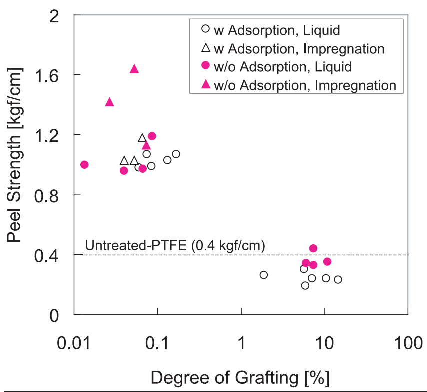

Fig. 3 Peel strength of (Cu+Cr) / AAc / PTFE as a function of degree of grafting.

3.2 Dielectric constant

The dielectric constant measured by a resonance cavity method is shown in Fig. 4. The dielectric constant of the PTFE film before the surface treatment is 2.13. When the degree of grafting is less than 0.2 %, it is seen that the values of the dielectric constant are not significantly changed by the surface treatment. We think that the radiation grafting was carried out without changing the composition of the PTFE surfaces.

On the other hand, when the degree of grafting is more than 1 %, the values of the dielectric constant increase. We think it is because a lot of carboxyl groups have adhered onto the surface of the films.

3.3 Prototype using EF2 fabrication

In Fig. 5 (a), we show an example of a metal mask product fabricated by the EF2 fabrication technique. Note that the shape of the metal has a clear cross-section. In Fig. 5 (b), we show the height in the vertical direction of an antenna pattern formed on the fluorine resin surface by EF2 fabrication. The measurement in the vertical direction of the metal-plated surface was carried out using a laser microscope (Keyence Corp. model VF-7500). The traditional fluorine substrates, NPC-F220A with 0.254 mm thickness (Nippon Pillar Packing Co., Ltd.), were used in this experiment. The dielectric constant is 2.2 and the dielectric loss tangent is 0.0006 at the frequency of 12 GHz. The copper thickness is about 5 μm. It is seen that an ultrafine pattern

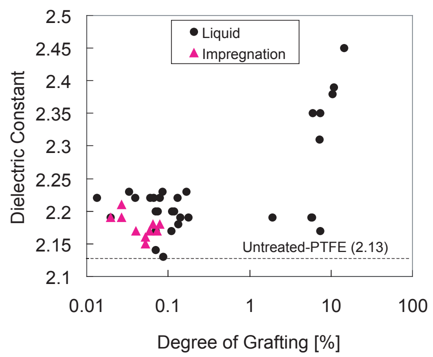

Fig. 4 Dielectric constant as a function of degree of grafting.

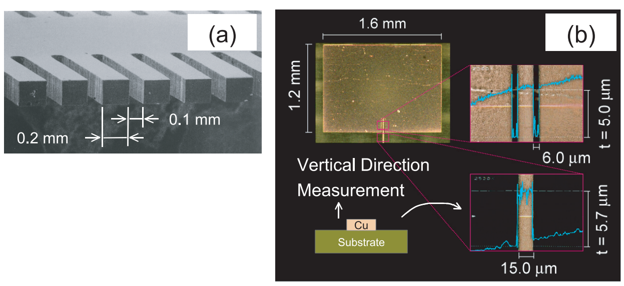

Fig. 5 The metal mask product (a) and the height in vertical direction of antenna pattern formed on fluorine resin surface (b) by EF2 fabrication.

with 6 μm gap width and 15 μm line width is formed.

3.4 Millimeter-wave antenna prototype

We designed an antenna pattern by CST Microwave Studio. The traditional fluorine substrates with 0.254 mm thickness were used for planar patch antennas in this experiment with the EF2 fabrication technique. The millimeter-wave antenna array has 240 elements and the size of the array is about 75 mm by 65 mm.

The measurement of the antenna radiation pattern was carried out by using a near-field measurement system (Tokai Techno Co., Ltd.) including a Vector Network Analyzer (37297C, etc. / Anritsu Co., Ltd.). The far-field pattern of the antenna is derived by conversion software.

Figure 6 shows the characteristics of antenna patterns at a frequency of 76 GHz. In Fig. 7 is shown the measurement of the antenna radiation pattern for various frequencies. The measured radiation patterns are in good agreement with the calculated one.

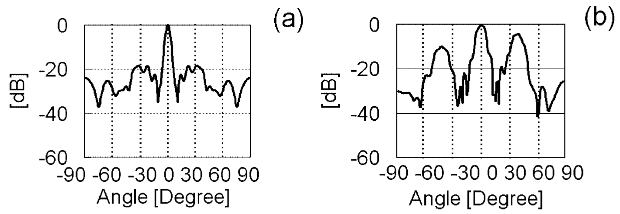

Fig. 6 Calculated far-field patterns at 76 GHz in H-plane (a) and E-plane (b).

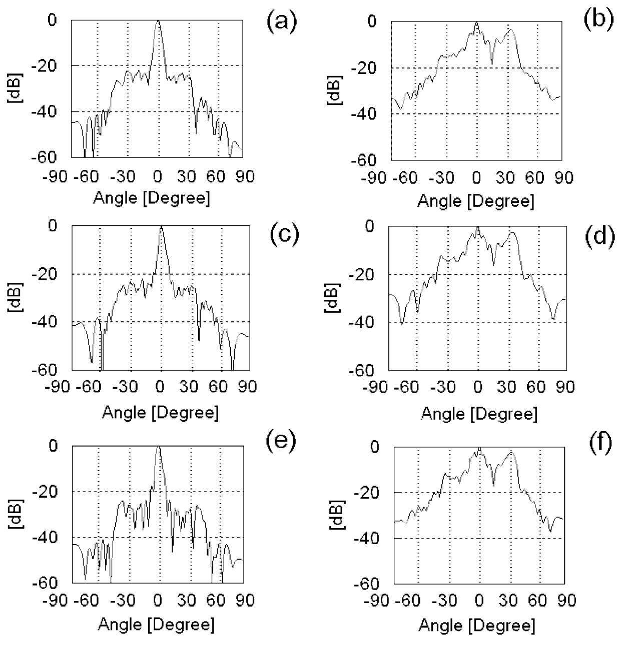

Fig. 7 Measurement of Relative Directivity at 75.5 GHz in H-plane (a) and E-plane (b) and at 76 GHz in H-plane (c) and E-plane (d) and at 76.5 GHz in H-plane (e) and E-plane (f) via near-field measurement system.

4. Summary

In summary, PTFE films were subjected to surface modification via radiation-induced graft polymerization using AAc. In general, the graft yield increased with the concentration of monomer used during graft polymerization and at the reaction time. The peel strengths of the sputtered metal to the PTFE films were significantly enhanced by the graft polymerization of the PTFE films using AAc. The achieved peel adhesion strength of PTFE was 1.64 kgf/cm. In addition, the values of the dielectric constant were confirmed to be not significantly changed. The prototype of a millimeter-wave antenna was designed and fabricated by using an EF2 technique. The measurements are in good agreement with the calculation.

In the future, the graft polymerization conditions, such as the dose, the monomer, the concentration, and the reaction time, will be optimized to achieve a further improvement in adhesion. Concerning the antenna radiation pattern, the level of sidelobe at the E-plane seems to be large. It is probably due to the reason that the spurious radiation has been generated owing to the reflection at any joint points. We have to reduce it to improve the performance of the antenna. As mentioned above, an ultrafine pattern can be formed on the fluorine substrate by EF2 fabrication after the surface treatment on the fluorine resin. We will develop low-loss millimeter-wave components, such as planar patch antennas, beam steering antennas, dual dipole antennas, and notch filters using EF2 fabrication for the improvement of millimeter-wave imaging diagnostics.

Acknowledgments

The authors with to thank the EF2 group of Kyushu Hitachi Maxell, Ltd. for their collaboration, and Mr. P. Cheyne for reading our manuscript. This work is partly supported by a Grant-in-Aid for Scientific Research, the Ministry of Education, Science, Sports and Culture ("Advanced Diagnostics for Burning Plasma" No. 16082205).

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