Investigation of rectenna for microwave power conversion

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Abstract
This paper presents the fabrication of organic semiconductor (OS) rectifiers and an investigation of rectifying antenna (rectenna) under the effect of microwave power. As a source of microwaves, a patch antenna fed by a generator was used. The rectenna contains a built-in rectifier. The surface-type Ag/NiPc/Au cell, with organic semiconductor nickel phthalocyanine (NiPc) as the active material, was used as a rectenna. The rectifier was fabricated by thermal deposition of Ag, Au and NiPc thin films on thoroughly cleaned glass substrate. The measured I–V characteristics of the cell showed rectifying behavior. The rectenna was tested at frequency ranges of 8–16 GHz at different intensities of radiation and vertical and horizontal positions of the rectenna’s axes. Under the effect of microwave power at the output of the rectenna, the output dc voltage and current were detected.

Keywords: rectenna, microwave power, nickel phthalocyanine, surface-type cell

Classification number: 4.10

1. Introduction
Conversion of solar energy into electric power by a rectifying antenna (rectenna) for the first time was suggested by Robert Bailey in 1972 [1]. This is one of the promising areas of technology and research for the utilization of solar energy [2, 3]. The potential energy conversion efficiency of the rectenna is estimated in the range of 80–90%. The important step in the development of technology of antenna-based solar cells and the conversion of microwave power into electricity was investigated in [4–6]. Good conversion of microwave power into dc was observed at 2.45 GHz: a dipole antenna array was connected with rectifier bridges and placed in the front of a microwave beam [2]. It was reported that the efficiency of the power conversion was about 84%.

Figure 1 shows a block diagram of the rectenna connected with the load [3]. The input low pass filter between the antenna and the rectifier is used (i) to prevent re-radiation by the antenna of harmonic waves produced by the rectifier, (ii) for impedance matching purposes between the antenna and circuit and (iii) to ensure a continuous current pass from the antenna to the rectifier. One of the most important parts of the rectenna is the rectifier. For optical frequency operation, very fast operation of the rectifier is required. It was found that an InGaAs-InP rectifier is able to rectify 50 GHz of electromagnetic radiation [3]. The metal–oxide–metal (MOM) or metal–insulator–metal (MIM) rectifiers, where the insulator is sandwiched between two metallic layers, are considered as most promising. In these devices, the tunneling of electrons from one metal to another metal takes place across the insulator film.

Organic semiconductor device technology is considered as a relatively cheap with respect to inorganic devices [7–9]. Nickel phthalocyanine is one of the organic semiconductors
Figure 2. Molecular structure of p-type organic semiconductor NiPc.

Figure 3. Schematic diagram of the rectenna with a built-in rectifier on the base of the NiPc: 1, glass substrate; 2 and 3, metallic arms of the rectenna; 4, film of NiPc; 5, gap between metallic films; 6, output electrodes of the rectenna.

that can be used for the fabrication of different kinds of sensors [10, 11]. The antenna with a built-in rectifier can be fabricated on the basis of organic semiconductors. In this paper, we have described the fabrication of a surface-type built-in rectenna Ag/NiPc/Au rectifier and the response of the rectenna under the effect of microwave power.

2. Experimental

The surface-type Ag/NiPc/Au cell, where NiPc is nickel phthalocyanine, was fabricated by thermal vacuum evaporator on a glass substrate at a pressure of $10^{-4}$ Pa. An Edwards AUTO 306 vacuum coater with diffusion pumping system was used for the fabrication of the rectenna. The NiPc powder used in this experiment was obtained from Sigma Aldrich. Its molecular structure is shown in figure 2. The sublimation temperature of NiPc varies from 400$^\circ$C to 450$^\circ$C. The substrate’s temperature in this process was held at $\sim$40$^\circ$C. The film thickness of NiPc, Au and Ag films were measured and controlled by an Edwards FTM5 film thickness monitor. The thickness and sizes (length and width of arms) of the metallic electrodes were 100 nm and 6 mm $\times$ 4 mm, respectively. The gap between the Au and Ag films was 40 $\mu$m. Thin film of thickness 100 nm of NiPc was thermally sublimated in the gape of two electrodes. Figure 3 shows a schematic diagram of the rectenna with a built-in rectifier on the base of the NiPc. From this figure it can be seen that this rectenna is a dipole antenna where the built-in rectifier is made on the arms of the antenna connected with the NiPc film. In this configuration, actually the rectifier will be connected parallel to the load with respect to the source. Although the rectifier’s dc output voltage is lower than in the case of traditional circuits where the rectifier is connected in series to the load with respect to the source, the former structure is easier to realize. In future work, the latter case will be developed as well.

The current ($I$)–voltage ($V$) characteristics of the sample and microwave energy conversion were investigated by conventional measuring instruments. As a source of microwave power, the HP-8350B Sweep Oscillator with an output frequency of 0.01–20 GHz and maximum power of 20 dBm was used. The oscillator was fed by coaxial cable to the patch transmitting antenna of the length and width of 13.04 mm and 9.64 mm (at 8 GHz), 11.75 mm and 9.6 mm (at 10 GHz) and 7.3 mm and 6.0 mm (at 16 GHz).

The maximum distance between the patch antenna and the rectenna was 25 cm. Different readings were taken at various intensities by keeping the power supply fixed and varying the distance between the source (transmitting antenna) and the rectenna. Figure 4 shows a schematic diagram of the experimental setup.

3. Results and discussion

Figure 5 shows the $I$–$V$ characteristics of the Ag/NiPc/Au cell. It is seen that the characteristics show the rectification behavior, which is a ratio of forward to reverse bias current and was in the range of 5–7 for the sample at $\pm$10 V, but it was 2.5 at $\pm$1 V. At forward bias, the positive potential was applied to the Au electrode. The reference Au/NiPc/Au and Ag/NiPc/Ag samples were fabricated where it was found that the $I$–$V$ characteristics were symmetrical and did not show rectification behavior. It is obvious that observed $I$–$V$ characteristics rectification behavior take place due to differences in Au and Ag work functions (5.1 and
4.3 eV, accordingly). The earlier investigations showed that phthalocyanines form ohmic junctions with Ag and Schottky type rectifying junctions with Al [12].

Figure 6 shows the dc output voltage–intensity of radiation relationships for the Ag/NiPc/Au sample at 10 GHz and the horizontal position of the sample axis (it would be parallel polarization of the electromagnetic waves with respect to the arms of the dipole antenna). It is seen that the output dc voltages increase with radiation intensity. It was found that in the vertical position of the rectenna’s axes, the output dc voltage in 15–25% is less with respect to the horizontal position of the rectenna’s axis. The dc current–intensity of the radiation relationship was analogous of the output dc voltage–radiation characteristics. The dc currents were in the range of 0.01–1 mA.

Figure 7 shows the dc output voltage–frequency relationship for the Ag/NiPc/Au sample at an intensity of radiation of 0.1 W m⁻². It is seen that the voltage–frequency relationship shows a maximum at a frequency of 10 GHz. Actually the experiments were conducted at the frequencies of 8, 10 and 16 GHz or accordingly at the microwave wavelength of 3.8, 3 and 1.9 cm, respectively. The observed maximum in the relationship shown in figure 7 may be explained by the selectivity of the antenna as a resonant device and the total length of two antenna’s arms is equal to 12 mm, which is very close to a half wave (15 mm) at a frequency of 10 GHz.

As is known [13], there are two antenna field zones: the Fresnel zone or near field and the Fraunhofer zone or far field. These zones are located near the antenna and at a large distance from the antenna, respectively. In the far field, the electromagnetic power is flowing from the antenna in a radial direction, whereas in the near field, the power flow is not entirely radial and depends on the shape of the antenna. The radius $R$ of the near field is determined by [13]

$$R = \frac{2L^2}{\lambda},$$

where $L$ is the maximum dimension of the antenna (m) and $\lambda$ is the wavelength (m). Taking into account the maximum dimension of the patch antenna and the value of the wavelength, it can be stated that the experiments were conducted in the far field.

The obtained results show that the rectenna is sensitive to the microwaves’ polarization and frequencies. An organic semiconductor NiPc based rectifier in the rectenna provides an output dc voltage that is low. Therefore, a number of measures should be realized to improve the properties of the rectifier and the rectenna as well: (i) to increase the rectification ratio at low voltages, the gap between the metallic electrodes should be decreased down to 100–200 nm, if the rectenna is to be used in visible spectra, for these purposes the nanotechnology should be used properly, (ii) the shape of the rectenna’s arms should be changed to make the rectenna effective in the circular polarization and a sufficiently wide band of incident electromagnetic waves; for example, the spiral antenna [2, 13] can be selected as a prototype, (iii) as an organic semiconductor, the donor–acceptor combination of two semiconductors; for example, p-type and n-type semiconductors may be used to make a bulk heterojunction [14] that is more effective than single or layered structures for use in the rectifiers.

4. Conclusion

The built-in organic semiconductor Ag/NiPc/Au rectifier of the rectenna was fabricated by thermal evaporation. The $I$–$V$ characteristics of the cell showed rectification behavior. The rectenna was tested at frequency ranges from 8 to 16 GHz, at different intensities of radiation, vertical and horizontal positions of the rectenna’s axes. Under the effect of microwave power at the output of the rectenna, the dc voltage and current were detected.

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