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月面洞窟内作業ロボットへの無線電力伝送に向けた GaN 整流素子の適応検討

Feasibility Study of GaN-based Rectifier for Power Transfer to Rovers Working in Lunar Caves

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1. Introduction

In 2009, observation of “KAGUYA (SELENE)”, JAXA’s moon orbiting satellite, revealed the existence of a large cavern, about 50 kilometers long and 100 meter wide, beneath the Moon's surface, which was located in an area called “Marius Hill” on the front side of the Moon. It also indicated that ice and water were possibly present in the stratum of the Moon. Therefore, exploring in the cavern will be essential for future usage of the lunar surface. For large-area explosion in the cavern, working rovers will be used. However, energy supply of the rovers is one of issues to be solved since they must be deployed over the large area.

Our proposed way of energy supply mainly consists microwave/millimeter-wave wireless power transfer and its mesh network as shown in Figure 1. Electrical energy generated with solar cells on the lunar is transferred down to the cavern by wire, and then is distributed to each small exploring rovers using microwave/millimeter-wave wireless power transfer. For realization of this system, one of technologies which should be developed is wireless power-receiving rectifiers due to the lack of applications on the ground.

In this presentation, we will introduce feasibility of millimeter-wave GaN rectifier device to the proposed idea for explosion of the cavern on the lunar, i.e., design of the GaN rectifier, study of power transfer with antennas. This have been studied in of “The 6th Tsnsa X, idea type research project” funded by Space Exploration Innovation Hus Center, JAXA.

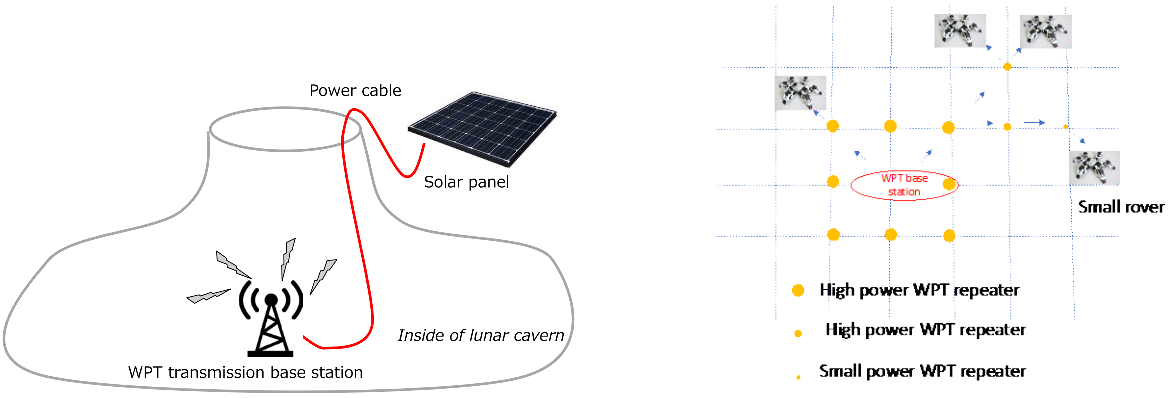

Figure 1. Schematic of proposed WPT for small rovers in lunar cavern.

2. Feasibility Study of GaN-based Rectifier for Power Transfer to Rovers Working in Lunar Caves

2.1. Design of GaN field-effect transistor (FET) based rectifier for millimeter-wave wireless transfer

A GaN field-effect transistor (FET) based rectifier, a gated-anode diode (GAD)[1,2], which can be operated under millimeter-wave frequency range was designed using a two-dimensional semiconductor device simulation, Silvaco ATLAS. A semiconductor epitaxial structure consists of a 15-nm thick GaN cap, a 1-nm thick a delta-doping region, a 1-nm thick unintentionally dope GaN, an 8-nm thick AlGaN layer, a 0.5-nm thick unintentionally doped-GaN layer, and carbon doped GaN layers (Figure 2). Although two ohmic electrodes and a Schottky electrode are on the epitaxial layers as same as the electrodes of a field effect transistor, one of the ohmic electrode is connected to the Schottky electrode for diode operation. In addition, for diode operation in the structure, the field effect transistor must have normally-off characteristics. For this requirement, the thickness of the AlGaN layer (8 nm) is much thinner than that for a conventional GaN HEMT of approximately 25 nm.

One of features of this rectifier is high power and high frequency operation due to advantages of a wide bandgap of GaN, a high electron mobility of two-dimensional electron gas generated at an interface between AlGaN/GaN and small anode capacitance with a short gate electrode.

Figure 3 shows a cut-off frequency (f_c), i.e, the maximum operational frequency of the diode, dependence on the anode length (a gate length in the transistor, L_g). The f_c is given by

$$f_c = \frac{1}{2\pi\, R\, C}, \qquad (1)$$

where C and R are an anode capacitance under the off-condition and a series resistance of the diode, respectively. In this figure, the GAD can be operatable at over 100 GHz.

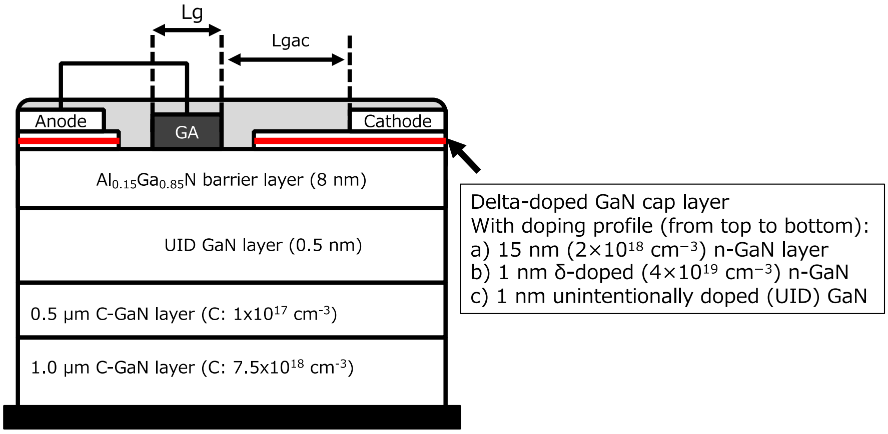

Figure 2. A cross-sectional structure of a GaN field-effect transistor (FET) based rectifier, a gated-anode diode (GAD).

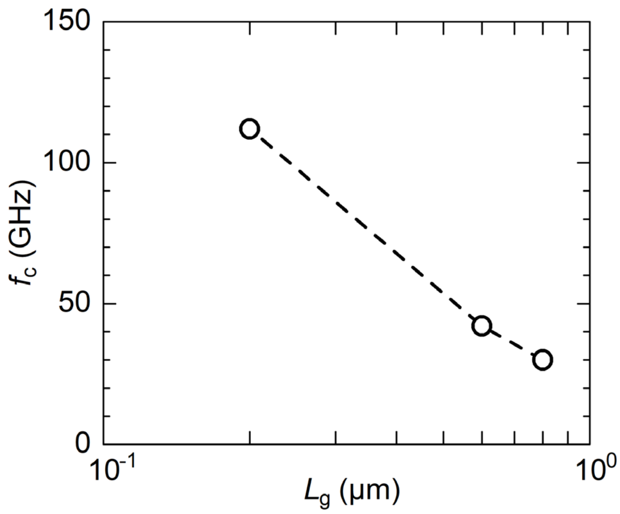

Figure 3. Dependence of f_c on L_g of the GaN GAD.

2.2. Specifications of small rovers working in lunar caverns

We investigated usage for wireless power transfer in lunar caverns. Figure 4 is a summary of specification of rovers and of the WPT systems. Initially, we roughly assume that power possibly generated on the lunar is limited less than 3 kW. On the other hand, a maximum power consuming in rovers is supposed to be several Watts when considering that a small and light weight rovers (～1000 cm^3 and a couple of hundreds grams) has a small motor for explosion, a wireless communication module and a sensor for soil component composition. Also, a distance between a power supply base station to rovers in charging is expected to be up to hundreds of meters, so that rovers will be able to do make some activates such as sensing after charging.

In this power transferring system, a size of power transmitting and receiving antennas are also restricted to 2 meters and 10 cm, respectively. With this size restriction, Friis's law

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 G_t\, G_r\,, \tag{2}$$

gives us how much power reduction occurs between the transmitting and the receiving antenna depending on the distance. Here, Pr and Pt are a receiving and a transmitting powers, G_r and G_t are gains of a receiving and a transmitting antenna, and λ is a wavelength. Figure 5 indicated relative power between the transmitting antenna with a G_t of 24 dBi and a receiving antenna with a G_r of 17.6 dBi at 24 GHz, which were reported in literatures[3,4]. Although the frequencies in the literatures are different from 24 GHz, the antennas ware selected within the above-described size-restriction assuming that the size of the antenna is inversely proportional to the frequency.

Assumption of specifications of small rovers on lunar

- Size: 100 cm3
- Weight: 100 g
- Constitution: Small motor, sensor, and wireless communication module
- Maximum power consumption: Watts

Assumption of specifications of WPT system

- Distance of power transfer: tens to hundreds meters
- Bas: 3.7 to 4.1 V unstable
- Capacity of battery: 3600 mAh

Figure 4. Summary of assumed specifications of small rovers on lunar and WPT systems.

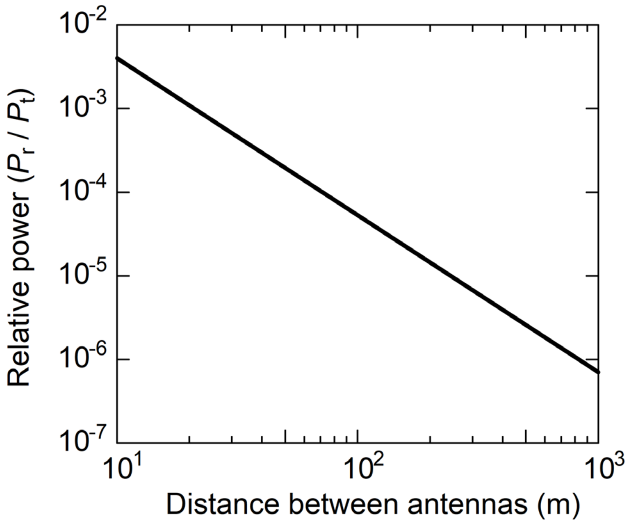

Figure 5. Relative received power (Pr) dependence on distance between antennas of Ref. XX and XX

3. Summaries

We have proposed the idea for explosion of the cavern on the lunar, i.e., design of the GaN rectifier, study of power transfer with antennas. We roughly assume that power possibly generated on the lunar is limited less than 3 kW. On the other hand, a maximum power consuming in rovers is supposed to be several Watts when considering that a small and light weight rovers (～1000 cm^3 and a couple of hundreds grams) has a small motor for explosion, a wireless communication module and a sensor for soil component composition. Also, a distance between a power supply base station to rovers in charging is expected to be up to hundreds of meters, so that rovers will be able to do make some activates such as sensing after charging.

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