Postprint: Langmuir Probe Performance Testing Using Semiconductor Diode I-V Characteristics

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Abstract

This study discusses a method for testing Langmuir probe performance using the I-V characteristics of semiconductor diodes. The designed Langmuir probe performance testing method imposes minimal requirements on external factors and can be conducted in a typical laboratory environment at room temperature and atmospheric pressure; its test results can serve as preliminary performance verification prior to calibration testing using ground plasma environments. The validity and feasibility of the method were verified through experimental testing in a laboratory environment.

Full Text

Study on Using Semiconductor Diode Volt-Ampere Characteristics for Langmuir Probe Performance Testing

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Abstract

This paper presents a technique for testing Langmuir probe performance using the voltage-current characteristics of semiconductor diodes. The Langmuir probe is an important instrument for in-situ detection of space plasma, and performance testing is critical to ensure its technical specifications meet mission requirements. The proposed method imposes minimal demands on external factors and can be implemented in a standard laboratory environment. Its test results can serve as preliminary performance verification before conducting calibration tests in ground-based plasma environments. The effectiveness and feasibility of this method have been validated through laboratory testing.

Keywords: Langmuir probe, performance test, V-I characteristic, semiconductor diode

0 Introduction

During China' s 12th Five-Year Plan period, research was conducted on an electromagnetic monitoring experimental satellite designed to acquire global observations of electromagnetic fields, plasma, and high-energy particles. This satellite aims to identify electromagnetic, ionospheric, and high-energy particle anomalies associated with major earthquakes, thereby exploring new methods for short-term earthquake prediction and early warning. As one of the scientific payloads, the Langmuir probe will be employed for space plasma detection, measuring in-situ parameters such as electron density and electron temperature to provide information on ionospheric plasma electron anomalies during the short-term period preceding large earthquakes.

In the design and development of Langmuir probes, instrument calibration is essential to ensure performance specifications meet mission requirements. Calibration experiments typically utilize ground-based plasma equipment to generate plasma that approximates the space plasma environment at satellite orbital altitudes. The Langmuir probe sensor is then immersed in this plasma environment, and the measured plasma parameters are compared with known set values to calibrate its performance indicators.

However, calibration using plasma environments involves long cycles, high complexity, and significant costs, and is generally conducted only after instrument development is complete. This makes it difficult to monitor performance status during the development process, creating a risk that final calibration results may fail to meet mission requirements. To enable preliminary performance testing and verification during development, this paper proposes a method that uses semiconductor diode volt-ampere characteristics for Langmuir probe performance testing. This approach can be implemented in a laboratory environment, and its test results provide important auxiliary support for subsequent development and plasma environment calibration.

1 Basic Principles of Langmuir Probes

The working principle of a Langmuir probe involves immersing a sensor into plasma, where it collects electrons and ions, forming a current. When a scanning voltage is applied to the sensor, the collected plasma current varies with the applied voltage, yielding a volt-ampere characteristic curve that reflects the interaction between the sensor and plasma. By analyzing this V-I characteristic curve, plasma parameters such as density, temperature, and plasma potential can be determined.

1.1 Langmuir Probe V-I Characteristics

The Langmuir probe V-I characteristic curve, shown in [Figure 1: see original paper], can be divided into three distinct regions: ion saturation region, retardation region, and electron saturation region. When the applied scanning voltage potential is below the plasma potential (relative negative potential), the sensor repels electrons and attracts ions. As the applied voltage decreases further, the ion current increases while the electron current decreases exponentially, with its contribution to the total collected current approaching zero. In this regime, the collected current can be considered entirely ion current, and this region is called the ion saturation region.

When the applied scanning voltage potential gradually increases relative to the plasma potential (shifting toward positive values), the electron repulsive field weakens while ion attraction strengthens. The sensor collects increasing electron current and decreasing ion current, with electron current gradually becoming dominant. This region is called the electron retardation region, where the collected electron current varies exponentially with scanning voltage.

When the applied scanning voltage potential exceeds the plasma potential, the sensor attracts electrons while repelling ions, forming an electron sheath around the sensor. Since electron current is inherently more than an order of magnitude higher than ion current, as the applied voltage increases further, the sensor collects more and more electrons while ion collection becomes negligible. The collected current in this regime is essentially pure electron saturation current, and this region is called the electron saturation region.

1.2 V-I Characteristics in the Electron Retardation Region

Assuming that space plasma particles follow a Maxwellian distribution, with no particle interactions and no strong magnetic field interference, the functional relationship between the collected current, applied bias voltage, and plasma parameters (electron temperature, electron density, ion temperature, ion density, etc.) can be expressed as:

In the electron retardation region, the collected electron current varies exponentially with scanning voltage. Since ion current can be neglected in this region, the sensor’ s collected current can be expressed as:

where I is the probe sensor’ s collected current, V is the applied scanning voltage, k is the Boltzmann constant ($1.38\times10^{\ 23}$ J/K), T_e is the plasma electron temperature, and e is the electron charge ($1.6\times10^{\ 1}$ C). I_{e0} represents the electron thermal current, where $I_{e0} = \frac{1}{4} e n_e \bar{v}_e A$, with $\bar{v}_e$ being the average electron thermal velocity, n_e the plasma electron density, e the electron charge, and A the sensor’ s electron collection area, which can be approximated by the sensor’ s geometric area (the portion effectively immersed in plasma).

Taking the logarithm of both sides of equation (2) yields:

where I_{e0}, k, and e are constants. Therefore, after obtaining the scanning voltage V and sensor collected current I, the plasma electron temperature T_e can be determined through calculation.

2 Semiconductor Diode Characteristics

A semiconductor diode consists of a PN junction with electrodes extracted from the P and N regions, encapsulated in a package. The physical structure and electronic symbol are shown in [Figure 2: see original paper] and [Figure 3: see original paper].

2.1 PN Junction V-I Characteristics

Through doping processes on a semiconductor crystal, P-type and N-type regions are formed on opposite sides. At the interface between these regions, a thin layer of positive and negative ions creates a space charge region, also known as the depletion region or barrier layer, forming a PN junction as shown in [Figure 4: see original paper].

The PN junction V-I characteristic curve, shown in [Figure 5: see original paper], exhibits three distinct behaviors: forward characteristic, reverse characteristic, and reverse breakdown characteristic. When forward voltage is applied, the PN junction conducts, presenting low forward resistance. Larger forward voltage yields greater forward current, with an exponential relationship between them. Under reverse voltage, the PN junction cuts off, presenting high reverse resistance. The reverse current, formed primarily by minority carrier drift, remains essentially constant with increasing reverse voltage and is thus called reverse saturation current I_s. When reverse voltage increases to a certain threshold, reverse current suddenly increases, causing reverse breakdown. The reverse voltage required to induce breakdown is called the reverse breakdown voltage V_{BR}.

In summary, the PN junction exhibits unidirectional conductivity, with its V-I characteristic expressed as:

where I is the current through the PN junction, V is the applied voltage across the junction, V_T is the thermal voltage given by $V_T = \frac{kT}{e}$, with k being the Boltzmann constant ($1.38\times10^{\ 23}$ J/K), T the thermodynamic temperature (absolute temperature), and e the electron charge ($1.6\times10^{\ 1}$ C). I_s is the reverse saturation current, which typically ranges from 10 to $10^{\ 1}$ A for discrete devices.

2.2 Diode V-I Characteristics

The actual diode V-I characteristic, shown in [Figure 6: see original paper], is essentially identical to that of the PN junction. Generally, the PN junction

V-I characteristic equation is used directly to describe diode behavior. However, due to factors such as diode dimensions, materials, and current values, the diode equation differs slightly from the PN junction equation. An emission coefficient n is introduced in the exponential term to represent actual characteristics:

where I is the current through the diode, V is the applied voltage, V_T is the thermal voltage, and I_s is the reverse saturation current. The emission coefficient n is an empirical constant ranging from 1 to 2, determined primarily by diode material and physical structure. For integrated circuit diodes, $n \approx 1$, while for discrete diodes, $n \approx 2$. When $n = 1$, the "1" in equation (5) can be neglected, yielding an exponential relationship between diode current I and applied voltage V:

Taking the logarithm of both sides gives:

where I_s, n, k, and e are constants. Therefore, given the applied diode voltage V and current I, the thermodynamic temperature T of the environment can be determined through calculation.

Analysis of equations (3) and (7) reveals that the principle for deriving plasma electron temperature from Langmuir probe V-I characteristics is identical to that for deriving environmental temperature from diode V-I characteristics. Consequently, testing diode V-I characteristics can simulate Langmuir probe behavior and verify preliminary probe performance.

3 Experimental Validation

3.1 Experimental Setup

Based on the above analysis, diode V-I characteristics can be used for Langmuir probe performance testing. [Figure 7: see original paper] shows the Langmuir probe measurement circuit. Replacing the sensor with a diode and resistor network yields the test circuit shown in [Figure 8: see original paper].

In the experimental circuit, a discrete diode 2CK75D was selected as the test device, with resistors R1 and R2 serving as current-limiting protection resistors. A scanning voltage ranging from -2 V to +4 V was applied through the scanning voltage unit, and an operational amplifier-based measurement circuit converted the diode current I into an output voltage V_{out}. The relationship between V_{out} and I is:

When the scanning voltage is negative, the diode is in reverse cutoff state, and current flows through resistors R1 and R2. When the scanning voltage is positive, the diode is forward-biased and conducts, with current flowing through the diode. By recording each scanning voltage V_s and its corresponding measured output voltage V_{out}, the diode' s V-I characteristic curve can be obtained.

3.2 Experimental Results

Laboratory testing yielded the diode V-I characteristic curve (semi-logarithmic coordinates) shown in [Figure 9: see original paper]. Analysis of this V-I characteristic curve yielded a thermodynamic temperature of 298.4 K (25.25°C) for the atmospheric environment during testing. The actual recorded ambient temperature during the experiment was 25.5°C (measured by thermometer). Considering measurement errors and temperature fluctuations during testing, the diode-based measurement successfully obtained accurate atmospheric temperature.

4 Conclusion

Analysis of both Langmuir probe and semiconductor diode V-I characteristics reveals that both exhibit exponential variation with applied voltage. Therefore, testing diode V-I characteristics can determine atmospheric temperature and thereby simulate Langmuir probe performance in measuring plasma electron temperature.

The method proposed in this paper can be implemented in a laboratory environment and successfully obtained accurate atmospheric temperature in testing. This approach can be applied for preliminary performance verification of Langmuir probes during development, playing an important role in technical improvement and performance refinement throughout the development process.

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