*Invited Paper*

# Mechanism and applications of weakly ionized plasma terahertz wave detector

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**Abstract**: Plasma generated in a discharged neon lamp has been successfully used for terahertz (THz) wave detection. However, the detection mechanisms are disputed. Some researchers advance that the THz wave enhances ionization current, and other researchers propose THz wave enhances diffusion current. We theoretically analyzed the detection mechanism, and found the electrons in the weakly ionized plasma could obtain energy from the incident THz radiation and convert excitation collisions of electrons with excited neutral atoms into ionization collisionsresulting in the increasing of the ionization current. An experiment was designed and testified the mechanism. Some applications of the weakly ionized plasma detector in electromagnetic wave detection and THz imaging were demonstrated.

**Keywords**: Terahertz wave, Plasma, Detector, Imaging

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## 1. Introduction

Recently, weakly ionized plasma (WIP) generated in a discharged neon lamp was successfully adopted for THz continuous wave (CW) detection with many merits including low cost, fast response time, large dynamic range, broad spectral range, and room temperature operation [1]. N. S. Kopeika has shown that the performance of glow discharge detectors (GDDs) is similar to that of pyroelectric detectors, with a noise equivalent power (NEP) on the order of $10^{-9}$ $W/Hz^{1/2}$ [2], and performed heterodyne detection for single GDDs and obtained much better sensitivity than in direct detection [3]. We have also investigated its unique characteristics by comparing with a Schottky diode and a pyroelectric detector in a THz interferometer [4], and have obtained THz images in a 4f imaging system and the results have shown that the image quality of the WIP detector is comparable with that obtained by a Schottky diode [5].

The detection mechanism of the WIP detector involves both enhanced ionization and enhanced diffusion current caused by the incident THz wave [6-9]. The former increases discharge current, while the latter decreases it. Ref. [8] indicates that the dominant detection mechanism is the enhanced ionization process leading to increase of discharge current. However, the experiment result in ref. [9] shows that THz radiation enhances diffusion current. To clarify the detection mechanism, in this paper, we theoretically analyzed the detection mechanism and then designed an experiment to testify it. Lastly, we demonstrated some applications of the WIP detector in electromagnetic wave detection and THz imaging.

## 2. Theoretical analysis

The motion of the electrons in the WIP can be described by (1) in the bias electrical field and THz field [10].

$$\frac{d\vec{v}(t)}{dt}+\frac{\vec{v}(t)}{\tau}=-\frac{e}{m}\vec{E}_{Loc}(t)\,, \tag{1}$$

where $\vec{v}(t)$ is the electron velocity, $\tau$ is the electron collision relaxation time, and $m$ is the electron mass. $\vec{v}(t)/\tau$ is the damping term, which is accountable for the energy transfer from electrons to inert gas atoms or ions by collisions. $\vec{E}_{Loc}(t)$ is the local electrical field, and $\vec{E}_{Loc}(t)=\vec{E}_{DC}+\vec{E}_{THz}(t)$, where $\vec{E}_{DC}$ is the DC bias electrical field. The $\vec{E}_{DC}$ leads to a constant discharge current which forms a DC background current. When the THz field applies on the WIP, the electron average kinetic energy increases [11] and the increment of electron's average velocity can be expressed as

$$\frac{d(\Delta\vec{v}(t))}{dt}+\frac{\Delta\vec{v}(t)}{\tau}=-\frac{e}{m}\vec{E}_{THz}(t)\,. \tag{2}$$

Suppose the polarization of incident THz wave is in $x$ direction, and it is expressed as $\vec{E}_{THz}(t)=\vec{E}_x=\vec{E}_0e^{j\omega t}$ . According to (2), the increment of electron's average velocity in $x$ direction can be expressed as

$$\Delta\vec{v}_x=\frac{e}{m}\left(\frac{\tau-j\omega\tau^2}{1+\omega^2\tau^2}\right)(1-e^{-(\frac{1}{\tau}+j\omega)t})\vec{E}_x\,. \tag{3}$$

In gas discharged plasma, there are existing trapped states in the high-lying Rydberg states in atoms and molecules [12]. Those trapped states can be easily transferred to ionic states via the collision with energetic electrons. From (2), after the electrons in the WIP are heated by the incident THz radiation THz radiation, electron-impact ionization of these trapped states leads to the increase of the ion population, which results in the increase of discharge current density between the electrodes. So the increment of current density caused by THz wave is expressed as

$$\Delta J=ne\Delta\vec{v}_x=\frac{ne^2}{m}\left(\frac{\tau-j\omega\tau^2}{1+\omega^2\tau^2}\right)(1-e^{-(\frac{1}{\tau}+j\omega)t})\vec{E}_x\,, \tag{4}$$

where n is the electron concentration in the plasma.

## 3. Experimental verification

To testify the THz wave enhancing the discharge current in the WIP, we designed an experiment, and the experiment schematic is shown in Fig. 1.

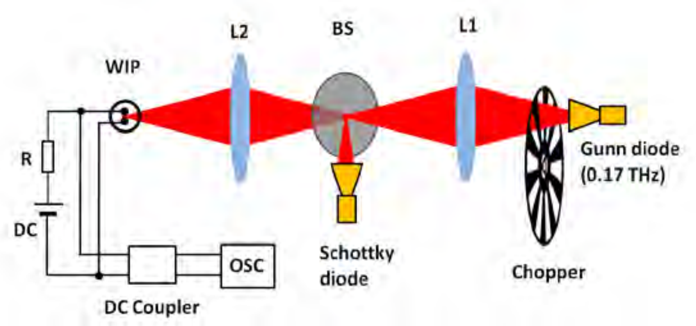


Fig. 1 Experiment setup for testing the effect of THz wave on the discharge current.

The WIP detector was made by a neon lamp (NE-2B-3×8 from www.allspectrum.com). The neon lamp was biased by a DC power supply to break down the inert gas. A 500 *nm* gold film, as a metal reflector, was deposited on one side of the neon lamp by e-beam evaporation to semi enclose the surface. The metal reflector can effectively increase the responsivity by reflecting and refocusing the transmitted THz wave on the electrode gap. The THz wave with the frequency of 0.19 *THz* generated from the Gunn diode (Virginia Diodes, Inc.) is focused by a HDPE lens (L1), and a high resistance silicon wafer is put at the focus as a beam splitter (BS). The transmitted beam is focused on the WIP by another HDPE lens (L2), and the reflected beam, as a reference beam, is received by a Schottky diode. The output signals from the two detectors are measured by an oscilloscope (OSC), which is shown in Fig. 2. The chopping frequency is 1080 *Hz*, and the “on” and “off” state of THz wave chopped by a chopper is marked on the waveform from the Schottky diode. The Schottky diode outputs a negative voltage when it receives THz radiation. Because the two signals are in phase, the voltage on the WIP detector decreased when it was illuminated by THz wave. However, it does not mean that the current through the WIP detector also decreased under the illumination of THz wave.

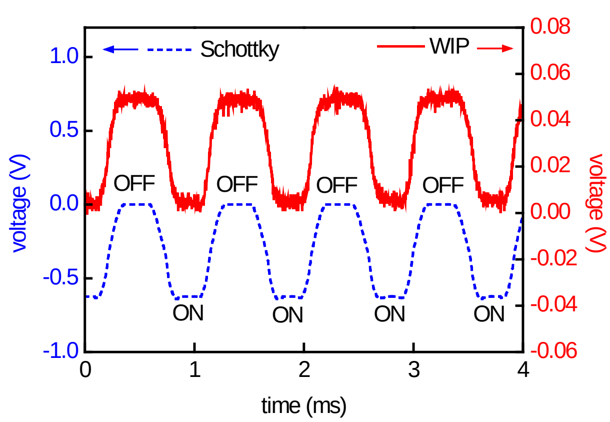


Fig. 2 Detected THz signals from Schottky diode and weakly ionized plasma detector.

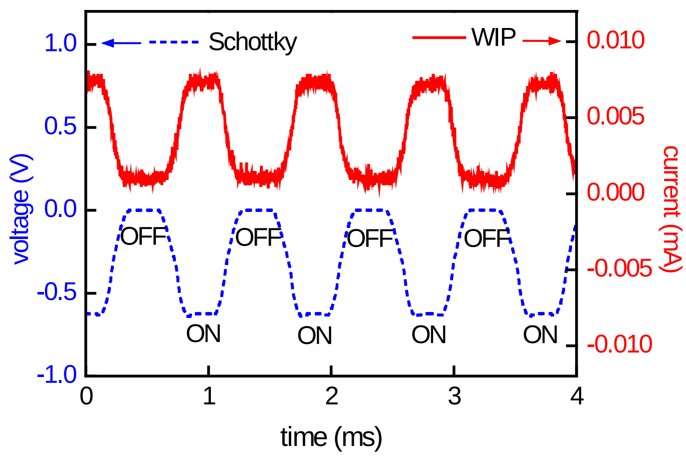


Fig. 3 THz signals from Schottky diode and the current increment in weakly ionized plasma detector illuminated by THz wave.

In the testing circuits, the voltage from the voltage source is 112 *V* and the current limiting resistor (R) is 7 *kΩ*, so the current variation through the WIP is obtained by

$$I = \frac{U - U_{WIP}}{R} - I_{DC}, \tag{5}$$

where $I_{DC}$ is the current caused by DC bias voltage, $U$ and $U_{WIP}$ are the voltage of the DC power supply and the voltage applied on the WIP, respectively. Fig. 3 illustrates the time varying discharge current in the WIP detector caused by chopped THz wave. It is clearly shown that the discharge current increases when the detector is illuminated by THz wave, which testifies that THz wave can increase the ionization rate of inert gases and then increase the discharge current.

## 4. Applications of WIP detector

(1) Wideband electromagnetic wave detector

The plasma frequency [13] of WIP detector can be calculated by

$$f_{pe} = \frac{1}{2\pi}\left(\frac{e^2 n_e}{\varepsilon_0 m_e}\right)^{1/2}, \tag{6}$$

where $\varepsilon_0$ is the permittivity in vacuum, $e$, $n_e$ and $m_e$ are the charge, concentration and mass of electron, respectively. In the WIP detectors, the electron concentration is in the order of $10^{16}/m^{-3}$, so the $f_{pe}$ is about 0.9 GHz. When the frequency of electromagnetic waves is lower than 0.9 *GHz*, they cannot permeate the WIP. Otherwise, the electromagnetic wave can pass through and interact with the WIP, so the WIP detector can be as a wide band detector to detect the electromagnetic waves with the frequencies of above 0.9 *GHz*.

Firstly, we illustrated the wide spectral response range of WIP detector at THz band. Two backward wave oscillators (Microtech instruments, Inc), which emit 0.1 *THz* (6.3 *mW*) and 0.37 *THz* (29 *mW*) continuous waves, and a Gunn diode (Virginia Diodes, Inc.), which emits 0.19 *THz* continuous wave (40 *mW*) were used. The signals from the WIP detector are tested by an oscilloscope with 64 times average. The chopping frequency is 200 *Hz*. Fig. 4 shows the detected results, and the results are normalized by THz power, that is, the signal voltages are divided by THz power. The responsivity of the detector at 0.1 *THz*, 0.2 *THz* and 0.37 *THz* are 0.98 *V/W*, 0.3 *V/W*, and 0.14 *V/W*, respectively. The responsivity decreases with the increasing of frequency. One reason is that the THz absorption of WIP detector's glass wall increases with the increasing of frequencies. Another reason is that, with the THz frequency increases, the electrons obtain less energy and interact with inert gas ions before the THz electrical field changes its direction, which causes the responsivity decreases [14].

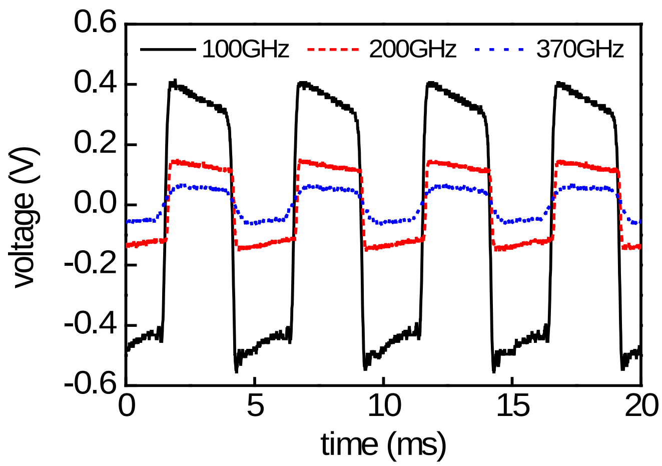


Fig. 4 THz signal (6.3 *mW* at 0.1 *THz*, 40 *mW* at 0.2 *THz*, and 29 *mW* at 0.37 *THz*) tested by WIP detector, the results were normalized by THz source power.

Then, we demonstrated that the response of WIP detector at optical band. In the experiment, a femtosecond laser (Rega, Coherent) and a hand held UV spot curing system (ELC-410, Edmund Optics) were applied as IR source and UV source. Fig. 5 shows the measured results of the IR signal. The wavelength and power of the IR beam are 800 *nm* and 350 *mW*, respectively. The IR beam was focused and illuminated on the WIP, and the signal from WIP detector was measured by an oscilloscope. The responsivity of WIP detector at 800 *nm* is as high as 13.5 *V/W*. Fig. 6 shows the measured results of the UV signal. The UV source has the wavelength of 200 - 400 *nm* and power of 90 *mW*. However, the light from UV source is emanative and difficult to be focused. The detector was placed close to the UV source, and the size of UV light is much larger than that of the detector, so less than 1 % of the UV energy was measured by the detector. Even in the adverse condition, the detector still shows good response.

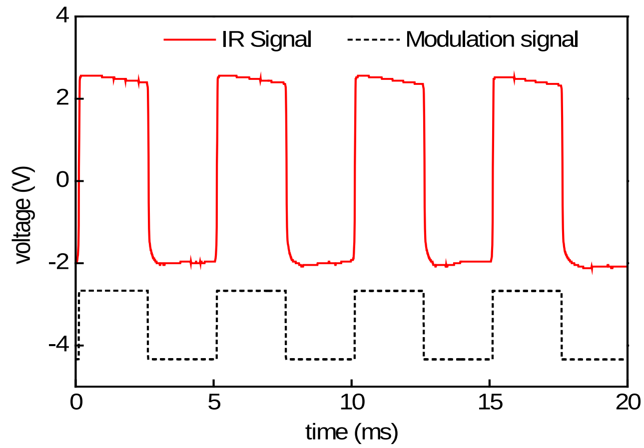


Fig. 5 IR signal tested by WIP detector. The chopping frequency is 200 *Hz*.

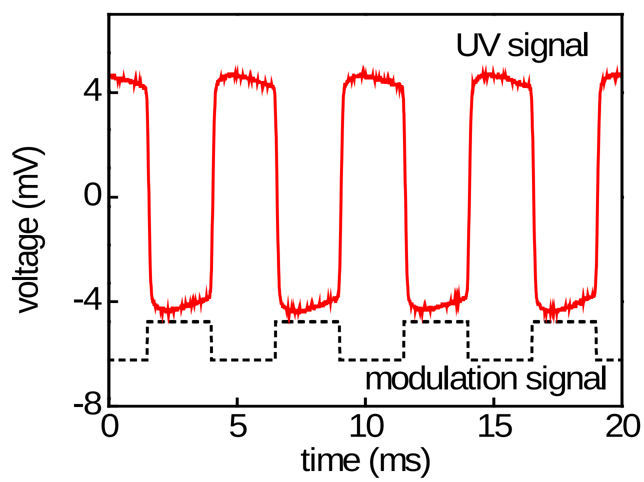


Fig. 6 UV signal tested by WIP detector. The chopping frequency is 200 *Hz*.

The detection mechanism of WIP detector is different at THz band and optical band. According to the analysis in section 2, the electrons obtain energy from THz wave and ionize more excited inert gas ions, which causes the discharge current increases. In optical band, the incident light can ionize inert gas ion directly, and the higher the frequency of incident light, the easier ionization of incident light [15].

(2) THz wave detector in THz imaging system

To show the ability of WIP detector, we built a raster scan 4f imaging system [16]. The THz source is the 0.19 *THz* Gunn diode. The beam was modulated by a mechanical chopper at 900 *Hz* and then was focused on the sample by a high-density polyethylene (HDPE) lens. After being transmitted through the sample, the THz beam was focused on the electrode gap of the WIP detector by another HDPE lens. The beam diameter at both the sample and the detector is about 2 *mm* detected by a pyroelectric array camera (OPHIR Photonics). A motorized scanning stage was used to raster scan the sample, and the intensity data were converted to a raster image.

(a) (b)

Fig. 7 Photo (a) and THz image (b) of a teapot with some water.

The imaging sample is a teapot with some water, and its photo and THz image are shown in Fig. 7(a) and Fig. 7(b), respectively. The spatial step of the sample scanning was 1 mm, the time constant of lock-in amplifier was 10 *ms*. Because the THz wave has a high transmissivity in ceramic and the THz power decreases with the increase of ceramic thickness, we can clearly see the internal structure of the sample. Whereas, the water has a high absorption to THz wave, so the water in the tea pot also can be seen. The result means that the WIP detector can be used in a THz imaging system for non-destructive testing.

(3) THz imaging focal plane array

Although THz raster scan imaging has high resolution, high contrast, but the speed is slow. To realize real time imaging, we fabricated THz focal plane array (FPA) based on micro-WIP detector. The inset of Fig. 8 is a sample of FPAs, which includes 9 FPAs with different electrode gaps and widths. It was made by photolithography and e-beam evaporation. The substrate is glass and the electrodes are made by 400 *nm* Ti and 1 $\mu m$ Au. The electrodes were biased by high voltage and grounded alternately, so the WIP can generate at every two adjacent electrodes. In the testing, we chose the middle FPA with the electrode width of 1 *mm* and electrode gaps of 1 *mm*, put it into a gas cell and filled neon with the pressure of 532 torr into the cell. A 190 *GHz* Gunn diode was used as a THz source, and it emitted 40 *mW* THz continue wave. The THz wave was expanded and collimated to a beam with the diameter of 10 *mm* and illuminated on the FPA with the size of 10 $mm \times 10$ *mm*. Fig. 8 shows the output signal from one of the array elements. The discharge current is 0.55 *mA*, and the bias voltage is 100 *V*. The results indicate that the FPA based on WIP is feasible, however, we also need to design data acquire system to realize imaging.

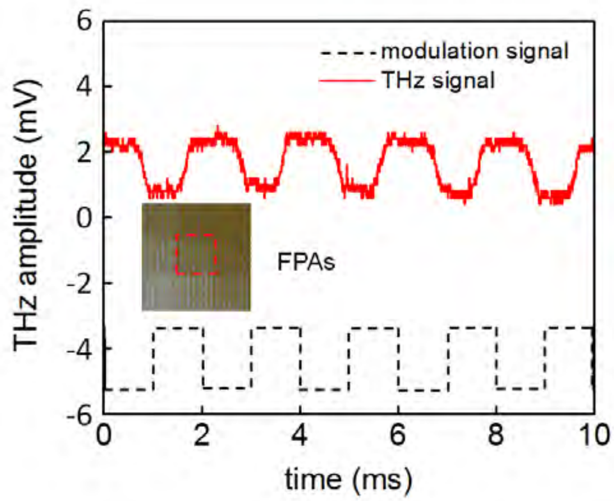


Fig. 8 Output signal from one of the array elements. The inset shows the structure of FPA, which are made by lithography and e-beam evaporation. The electrodes are made by Ti/Au. Ti: 400 *nm*, Au: 1 *μm*.

## 5. Conclusions

From the theoretical analysis and experimental result, we know that the detection mechanism of THz WIP detector is that the incident THz wave increases the energy of electrons, which converts the excitation collisions of electrons with neutral atoms into ionization collisions, and thus to increase the discharge current. We demonstrated that the WIP detector can test THz wave, IR and UV signal, and can be used in THz raster scan imaging system with good performance. WIP FPAs were prepared and the preliminary test shows that the device can be used in THz focal plane imaging.

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