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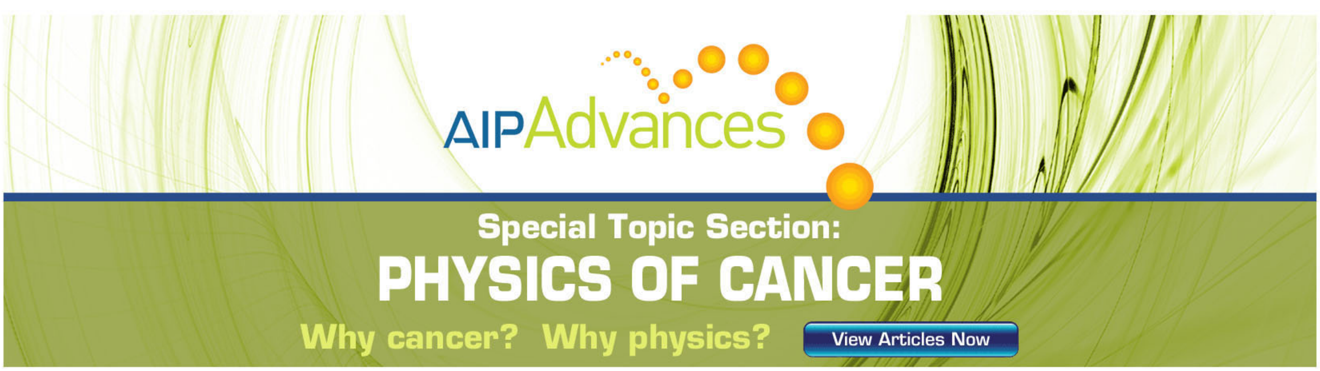

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# Terahertz detection mechanism of inexpensive sensitive glow discharge detectors

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The detection mechanism of glow discharge plasma, which is derived from direct current gas breakdown, in neon indicator lamps was investigated in the terahertz and microwave regimes. Such devices exhibit high sensitivity to terahertz radiation. Experimental setups at 10, 100, and 250 GHz were carried out and analyzed. The analysis of the experimental results shows that the dominant mechanism of the glow discharge detector (GDD) in these regimes is enhanced cascade ionization. Furthermore, the responsivity at 10 GHz decreases with the increase in the dc bias current between the electrodes, while the responsivity at 100 and 250 GHz increases with the dc current. This is attributed to electron-neutral atom collision frequency $(\nu)$ of the GDD being tens of gigahertz and its increasing with dc bias current according to dc field increase. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2917386]

## INTRODUCTION

The electromagnetic spectrum between 100 GHz and 10 THz becomes very attractive for applications in medicine, communications, homeland security, and space technology. There is no known ionization hazard for biological tissue, and atmospheric scattering and turbulence effect on terahertz radiation are low compared to that on infrared and optical rays. The lack of inexpensive but sensitive room temperature detectors in this spectral region makes it difficult to develop detection and imaging systems.

However, use of modern miniature neon indicator lamp glow discharge detectors (GDD) as pixels in terahertz and millimeter wave focal plane arrays is very attractive since they are very inexpensive and require no cooling. Their high sensitivity to terahertz radiation has been recently reported,[1] and it is similar to that of pyroelectric detectors and Golay cells. Green neon indicator lamps yield green instead of orange light due to green phosphor on the glass envelope. The phosphor coating increases the detected signal. In detector operation, the indicator lamps are biased with a direct current to break down the gas. The incident rf energy is amplitude modulated, with the GDD acting as an envelope detector. The detected signal is the modulation of the rf energy, which can be separated from the dc bias with a capacitor. Investigation of the modern GDD detection mechanism in the microwave and terahertz regimes is given in this paper. It was found that the detection mechanism is the enhanced cascade ionization, which causes an increase in discharge current, agreeing with the dominant mechanism in older model GDD devices.[2] Here, we found that the mechanism of detection is derived from enhanced ionizing collisions of electrons with neutral atoms generated by the incident rf electric field. According to this theory, the effect of the radiation is most pronounced where the total electron energy is at a maximum (around the cathode dark space). The addition of the rf electric field to the dc bias electric field then slightly increases the rate of ionization and excitation collisions beyond that provided by the dc bias. This is particularly a characteristic of the cathode dark space area adjacent to the cathode, where the dc electric field is maximum. The change in current density in the case of $\omega > \omega_p$ ($\omega_p$ is plasma frequency) is given by[2]

$$\Delta J \cong \frac{e^2 \times \eta_0 \times M \times \nabla n \times P_D}{3km^2(\omega^2 + \nu^2)}, \tag{1}$$

where $e$ is the electron charge, $\eta_0$ is the free space impedance, $M$ is the gas molecule mass, $n$ is the elecron density, $P_D$ is the radiation power on the detector, $k$ is Boltzmann's constant, $m$ is the electron mass, $\omega$ is the electromagnetic radiation frequency, and $\nu$ is the electron-neutral atom collision frequency.

Change in bias current charge caused by absorption of incident electromagnetic waves can be positive from enhanced cascade ionization collision rate or negative through diffusion, and is given by[3]

$$\Delta I_d = (\Delta \nu_i) \times n + \nu_i \times (\Delta n) - (\Delta D) \times \nabla^2 n - D \times \nabla^2(\Delta n), \tag{2}$$

where $\nu_i$ is ionization collision rate and $D$ is diffusion coefficient.

The signal electrons generated by the addition of the rf field can then participate in ionizing collisions with neutral atoms on their way to the anode, thus providing internal terahertz signal amplification. An overall expression for the change in bias current is given by.[4]

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$$\Delta I_d(t) = eVn[\Delta \nu_i(t)]\frac{\exp(2\nu_i t_d)}{2\nu_i t_d} = \frac{Ge^2V_n}{V_i m}\left(\frac{\tau}{\tau_i}\right)\eta_0 P_D\left(\frac{\nu}{\nu^2+\omega^2}\right)\left[1-\exp\left(\frac{-t}{\tau}\right)\right], \tag{3}$$

where $V$ is the discharge volume, $t_d$ is the average electron drift time to the anode. $\tau$ is detection time constant, $\tau_i$ is the average interval time between two rf electron ionizing collisions, and internal signal gain

$$G \approx \frac{\exp(2\nu_i t_d)}{2\nu_i t_d}. \tag{4}$$

Calculations indicate that such gain can be on the order of $10^6$.[4] According to Eq. (3), the response peaks when collision frequency $\nu$ is equal to $\omega$. With the modern green neon lamps, bombardment of the phosphor by signal electrons can give rise to additional green photons which can photoexcite or photoionize excited atoms, thus providing an additional signal gain.

## EXPERIMENTAL SETUP AND RESULTS

The detection mechanism of GDD was investigated here in three different spectral bands: 10, 100, and 250 GHz. The 100 GHz source is based on GaAs multipliers manufactured by Virginia Diode, Inc. (VDI) (Ref. 5) that multiply a low frequency source to 100 GHz. In our case, we use an ordinary 2–18 GHz synthesizer as a low frequency source and multiply it by 8 to obtain 92–102 GHz. Using this source, we can achieve power levels of 150–200 mW, depending on the required frequency.

The source at 250 GHz is based on a backward wave oscillator (BWO) which is part of a terahertz quasioptic system.[6] In this experimental setup, we used BWO catalog No. OV 24N123 operating at 173–260 GHz, which provides 20–30 mW, depending on the frequency.

The above sources for 100 and 250 GHz radiate in free space, and via a polyethylene (PE) lens, the terahertz radiation was focused on the GDD cross section between the electrodes. The basic experimental setup is given in Ref. 1. The 12.5 GHz signal of the rf synthesizer was amplitude modulated with a 1 KHz square wave. This modulated signal was used to drive the 8X GaAs multiplier. The 100 GHz radiation was coupled out by a rectangular horn antenna which produces an approximately fundamental mode of Gaussian beam.[7] The terahertz Gaussian beam was focused by a PE lens on the GDD. The GDD was operated in the abnormal glow region of the current voltage characteristics[4] and it was connected to an amplifier and to a scope (see Ref. 1). Since the modulation of the terahertz beam was 1 KHz, we tuned the bandwidth of the amplifier to be between 100 and 10 000 Hz in order to reduce the noise of the detection system.

The 1 KHz amplitude modulated 10 GHz source was directly obtained from the 2–18 GHz synthesizer using an $X$-band horn antenna. The radiation was collimated to the GDD lamp by a receiving $X$-band horn antenna, as shown in Fig. 1. The output signal was obtained on the scope and was recorded by a special computer code.

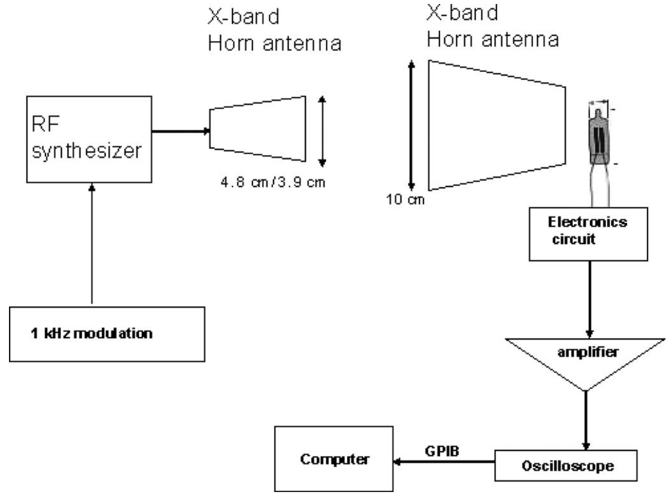


FIG. 1. Experimental setup for investigating GDD detection mechanism to $X$-band radiation.

A commercial green neon indicator lamp, N523,[1] of International Light Technologies (Peabody, MA) was used in these experiments as a GDD. The N523 showed the best performance as a terahertz detector among neon indicator lamps from several companies that were examined using the basic experimental setup of Ref. 1.

Detection signal of the modulated 10 GHz radiation at 9 mA dc current is shown in Fig. 2. The response of GDD N523 as a function of dc bias current at $X$-band (10 GHz) is given in Fig. 3.

The responsivity curve given in Fig. 3 decreases with increased in GDD dc current above 1 mA. This means that 10 GHz is below the electron-neutral atom collision frequency of the lamp [see Eq. (2)]. Moreover, it seems that the N523 GDD has a much higher electron-neutral atom collision frequency compared to lamps produced in the past. This may well be a result of much improved radioactive doping to improve ionization efficiency. Present day GDD indicator lamps produce much more light at lower currents than those manufactured 35 years ago.

The detection mechanism of the GDD from Fig. 4 was found to be the enhanced cascade ionization current. In ad-

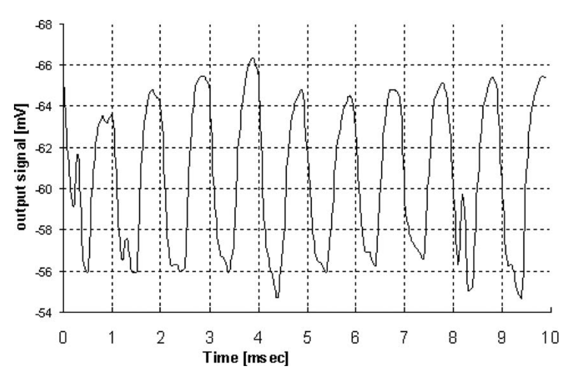


FIG. 2. GDD detection signal of 1 KHz amplitude modulation at 10 GHz. The GDD dc bias current was 9 mA.

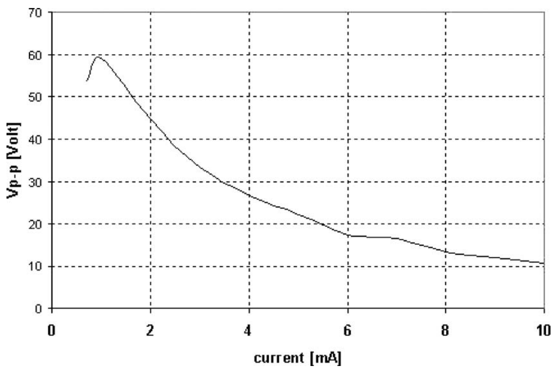


FIG. 3. Response of GDD N523 at 10 GHz measured at amplifier exit.

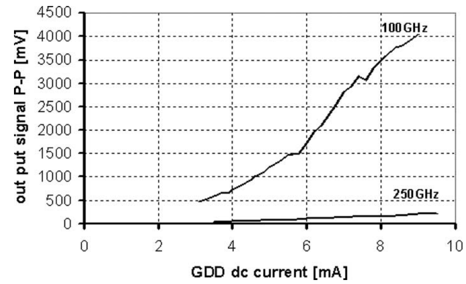


FIG. 5. Response of GDD at 100 and 250 GHz.

dition to the mechanism described above, this may also result from an increase in space charge in the Faraday dark region caused by the improved radioactive additive. rf radiation increases those electron energies and enables them to reach the anode. This causes enhancement in collision rates and increase in discharge current. The voltage across the GDD itself is lower when it is exposed to the rf radiation as a result of increase in discharge current and consequential increase in the voltage across the resistor (see electric circuit of Fig. 1).

The response curves of the GDD N523 for 100 and 250 GHz are given in Fig. 5.[1] Please note that the incident power at 250 GHz is one order of magnitude less than that at 100 GHz.[1]

Figure 5 shows that at 100 GHz, the higher the dc bias current of the GDD, the better is the responsivity of the GDD. This is attributed to the increase in electron-neutral atom collision frequency with bias current[2,4] according to dc electric field increase, thus increasing the responsivity of the GDD. The dc current in the GDD was controlled by changing the GDD dc bias voltage from 100 up to about 150 V (see Fig. 1).[1] The electrical parameters for the 100 GHz are as follows: amplification of 40 dB and electronic bandwidth of 100–10 KHz. The detection mechanism of the GDD in 100 GHz region is a positive current since the discharge current was increased and the voltage of GDD was decreased, as seen in Fig. 4. The response curve of GDD at 250 GHz is given also in Fig. 5. The experimental results were obtained under the following parameters: The BWO source was set to 250 GHz and power of 10–20 mW. The output frequency of the BWO is determined by the high voltage delivered to the cathode of the BWO. In this experiment, we used an external chopper to modulate the terahertz radiation to about 700 Hz.

To verify our assumption regarding the detection mechanism, we carried out orientation experiments with the GDD. In the first experiment, the electric field of the rf radiation was orthogonal to the dc electric field. In the second experiment, the electric field of the rf radiation was in the same direction as the dc electric field. The results show that in the second experiment the responsivity of the GDD was almost twice the responsivity of the first experiment, which suggests the major signal component stems from adding the rf electric field to the dc electric field to increase the electron inelastic collision rate. In the first experiment, the electric field of the rf radiation causes electrons trapped between the cathode and negative space charge region [Faraday dark region–negative glow] to diffuse out to the GDD walls. This negative signal current then decreases the positive enhanced ionization collision signal current. Those results confirm that the detection mechanism is the enhanced cascade ionization. The electrical parameters were the same in both experiments.

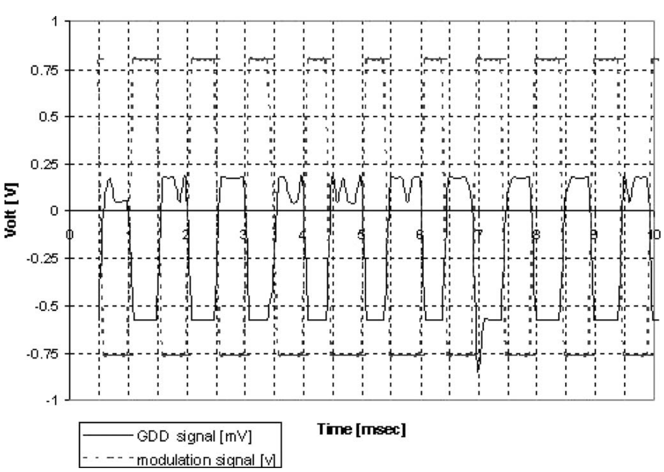


FIG. 4. GDD detected signal (solid line) and modulation signal (doted line) at $X$-band.

## DISCUSSION

Ambipolar diffusion is relevant here because $T_e > T_i$, where $T_i$ is ion temperature and $T_e$ is electron temperature. In such a situation, the diffusion constant $D$ is proportional to $\Delta J$ in Eq. (1).[3] Thus, rf field enhanced diffusion can increase when the rf field is orthogonal the dc field, which decreases the positive cascade ionization signal current. However, when the rf and dc electric fields are aligned, the rf field increases electron energy above that provided by the dc field, and thus increases inelastic collision rate of electrons with neutral atoms, thus increasing the discharge current. The cascade ionization signal current is therefore positive. Signal amplification is provided by the cascade ionization and by photoexcitation and photoionization caused by the green photons emitted by the phosphor.

## CONCLUSIONS

The detection mechanism appears to be in all three radiation frequencies enhanced cascade ionization (positive current) instead of diffused current (negative current). The former seems to occur in the cathode dark space where electron energy is maximum. The latter seems to occur in the Faraday dark area location of the GDD where the electrons have very low energy, most of the negative space charge gradient is concentrated, and diffusion current is known to arise.[3]

At *X*-band, the response decreases with increase in GDD dc current. It suggests that 10 GHz is below the plasma frequency of the lamp. At higher frequencies, the response increases when DC current is increased. Moreover, it seems that modern GDD devices such as the N523 have much higher electron-neutral atom collision frequency than previous generation lamps, and it increases with increase in the dc current according to electric field increase.

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