Analysis of Bow-Tie Au/Si₃N₄ and ITO/Si₃N₄ Terahertz Antennas

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Abstract

Bow-Tie Au/Si₃N₄ and ITO/Si₃N₄ antennas are designed and analyzed using the finite element, Multiphysics COMSOL program. The study shows that the electric field output is affected by the size of the antenna gap, the thickness of the antenna metal layer, the width, and the length of the antenna. The length of the antenna makes the most profound impact, where the resonant frequency decreases as the length increases. The Au antenna output is about 4 times the ITO antenna output. Integrating antennas with different lengths may allow for building wide band THz sensors arrays. The studied antennas can be easily integrated with microelectronic technology, due to the compatibility of the materials used.

Keywords: Bow-Tie Antenna; Terahertz antenna; THz sensors; ITO/Si₃N₄; Gold/Silicon nitride antenna; COMSOL

Introduction

Terahertz frequency falls between the microwave spectrum and infrared. THz spectrum can be used in many applications including, space observation, cosmic radar, material identification, biomedical imaging, security, communications, scientific instrumentations, and military applications [1-3]. One of the main advantages of THz radiation is that it is safe for medical applications, since it is a non-ionizing electromagnetic wave. Therefore, THz can be used in medical imaging without the fear of damaging tissues or DNA strands.

Traditionally, sensing THz can be done using bolometers [4-8], golay cells [9-12], pyroelectric detectors [8], and Schottky diode detectors [11]. A bolometer is a device that measures the incident power of an electromagnetic wave, such as THz. The way the bolometer works is that the incident power heats a heat-sensitive resistive element. The change in the element resistance can be related to the power of the incident signal. The amount of power absorbed depends on the input power and the absorbance coefficient. The absorbance coefficient depends on the wavelength. Hence one can relate the element temperature to the signal power and frequency. Operation of the bolometer requires the use of a heat sink with constant temperature, and the change in the element conductance results in signal detection [8].

Pyroelectric detectors are made using ferroelectric materials, such as lithium tantalite, whose electrical polarization changes with temperature, and this behavior can be used to detect THz signals [8]. Lithium tantalite has flat response with nano-watts sensitivity, but it can handle high power (50mW). The problem with this detector is that it is only sensitive to a time varying signal. Hence constant signals will not be easily detected. In addition, it is sensitive to temperature change not to wavelength [8].
Schottky diodes can be used for THz detection and mixing. When a THz signal is applied, a change in the voltage across the diode is detected. The diode voltage becomes \( V_d + \Delta V \), where \( \Delta V \) is related to the input signal. The diode current, in this case, becomes \( I_d = I_s \exp\left[\frac{q(V_d + \Delta V)}{kT}\right]^{-1} \), where \( I_s \) is the saturation current, \( k \) is Boltzmann constant, and \( T \) is the temperature in Kelvins. The change in the diode current is then related to the input signal [8,13].

Other THz detector antennas can be in the form of a dipole array [14], a spiral, or bow-tie antenna [2,3]. Bow-tie antennas have the advantage of small size, easy integration with other technologies, and the ability to be built as an array to provide the required power. A bow-tie antenna has a bow-tie shaped metal, deposited on top of a dielectric substrate. The performance of the antenna is affected by both the substrate dielectric strength and the metal conductivity.

THz systems, such as an imaging system, normally contain THz sensor arrays for detection and integrated circuits (ICs) for signal processing. THz sensor array is basically an antenna array. To build high performance systems, the sensor array needs to be integrated with a conditioning and processing circuits. In silicon technology, there are two main dielectric materials that are widely used: silicon dioxide (SiO\(_2\)) and silicon nitride (Si\(_N_3\)). Therefore, using SiO\(_2\) or Si\(_N_3\) as dielectric substrates would yield the most effective integration process. THz bow-tie antennas built on SiO\(_2\) have been studied [2,3,15]. However, bow-tie antennas built on Si\(_N_3\) still need further studies. In this study we design, simulate and analyze the performance of these antennas and compare their characteristics to the antennas built on SiO\(_2\).

### Antenna Design

Bow-tie nano-antennas built on Silicon Nitride is designed and analyzed using finite element numerical analysis in the THz range. Si\(_N_3\), which is the most thermodynamically stable of the silicon nitrides, is used. Si\(_N_3\) has energy gap of about 5 eV with high-melting-point and relative chemical inertness. Si\(_N_3\) has dielectric constant as high as 7.5, has very good insulation properties, and is widely used in ICs, Microelectromechanical systems (MEMS) and sensors [16,17].

Gold (Au) is normally used to build antennas. Gold is chosen because it is chemically inert and has a very high conductivity. However, Au is opaque in the optical spectrum. This limits its ability for vertical integration with optical/optoelectronic devices. To ensure the ability of vertical integration, transparent metals may need to replace Au. Because almost all-natural metals are opaque materials, it was decided to use a degenerate semiconductor as a metal for the antenna. Indium-Tin-Oxide (ITO) is a wide band gap, degenerate semiconductor with high conductivity and better transparency in the visible spectrum. In the THz range, ITO can absorb more than 90% of the incident signal, if the film is deposited using sputtering [18]. Bow-Tie antenna has been studied by many research groups [15,19-23]. They have shown that the antenna's performance is enhanced when the bow-tie shape is used.

![Figure 1(a): Bow-tie nano antenna used in the study. with 100 nm gap. 1(b) COMSOL simulation of the electric filed; intensity is highest across the gap.](image-url)

In this study, two types of bow-tie antennas were studied: Au/Si\(_N_3\) and ITO/Si\(_N_3\). The study was conducted using COMSOL, a commercial, numerical, multi-physics program [24]. The bow-tie antenna is basically two triangles with a nano-gap between their vertices, as shown in Figure 1. The antenna has 16 µm length, 9 µm width, and 1µm thickness. The gap is 100 nm between the two apexes.

The gap between the two triangles of the bow-tie dipole antenna affects the performance of the antenna, since it acts as a capacitor, where the distance between the two sides determines the value of the capacitance. This, in turn, determines the amount of charge accumulated and the potential, or the electric field, across the two apexes. The sharpness of the apexes also affects the density of the charge accumulation. In our case, it is assumed that we have a perfectly sharp tip. The electric field is typically concentrated at the gap of the antenna due to Coulomb field. The electric field across the gap is the antenna output. This output can be detected by measuring it directly or by applying it across a diode and measure the corresponding current of the diode. Since the diode...
current is an exponential function of the voltage across the diode, by measuring the change in the diode current, the output voltage can be determined. But, in this study, the output potential is measured directly without the aid of a Schottky diode.

The geometry, with the various boundaries that was used in COMSOL simulation, is shown in Figure 2. As can be seen from the figure, the antenna is placed on top of 20 µm Si₃N₄ substrate. On the top of the antenna, a 20 µm of air is placed. To avoid reflections from the top boundaries, a Perfectly Matched Layer (PML) with thickness of 10µm is placed on the top of the air region and under the bottom of the Si₃N₄ [2,3]. The electromagnetic wave (THz signal) is applied to the antenna vertically, using a COMSOL feature port that applied 1 V/m wave magnitude in the z-direction. The port is excited with an electric source placed at 20µm above the antenna metal, just below the upper PML layer.

In COMSOL, Maxwell equation is solved to obtain the output electric field across the gap. The differential equation used in this case is as follows:

\[ \nabla \times \mu^{-1} (\nabla \times E) - k_0^2 \varepsilon \eta E = 0 \quad (1) \]

where \( \mu_r \) is the relative permeability, \( \varepsilon_r \) is the relative dielectric constant, \( E \) is the electric field, and \( k_0 \) is the wave number = \( (\omega/c) \), where \( \omega \) is the radial frequency and \( c \) is the speed of light.

The dielectric constant of conducting materials, such as metals or degenerate semiconductors, is a frequency-dependent complex number. The dielectric constant can, then, be obtained from the Drude model [25] as:

\[ \varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - \omega_p^2 + i \omega \omega_d} \quad (2) \]

where \( \varepsilon_\infty \) is the permittivity at very high frequencies, which represents the contribution of the bound electrons to the relative dielectric constant, \( \omega_p \) is the plasma frequency, and \( \omega_d = \sqrt{\frac{q^2 n}{m' \varepsilon_\infty}} \) is the damping frequency, where \( q \) is the electron charge, \( n \) is the electron density in the conduction band, \( m' \) is the electron effective mass, and \( \varepsilon_\infty \) is the free space dielectric constant [15]. The dielectric parameter is a complex value, since it is frequency dependent, as shown in Equation (1). COMSOL uses Equation (1) to obtain the complex dielectric at various frequencies [26]. It should be noted that the dielectric constant for insulators is real, since \( \omega_p \) can be neglected because \( n \) is negligible in dielectric conduction bands. For metal, \( n \) is very large, which results in a complex dielectric constant.

### Results, Analysis, and Discussions

First, the performance of Au/Si₃N₄ antenna is investigated. The conductivity of Au is taken to be \( 45.6 \times 10^6 \) S/m and the dielectric constant to be \(-8.49+1.62 \) j. For Si₃N₄ the dielectric constant is taken to be 7. As shown in Figure 3, the antenna has two peaks: the first at about 2 THz and the second at about 4 THz. Figure 3 shows also the effect of the gap size on the output. The data show that, as the gap size increases, the output field decreases. This can be attributed to the decrease of the capacitance (C) between the two halves of the antenna, due to the increase of the gap. The decrease of the capacitance leads to the decrease of the charge accumulation, and consequently, to the decrease of the electric field.
The effect of the thickness of the metal antenna is investigated next. Figure 4 shows that as the metal thickness increases the electric field increases. This can be attributed to the fact that the increase of the metal thickness increases the conductivity. The increased conductivity increases the flow of the charges to the antenna tips, which, in turn, leads to the increase of the output voltage and the electric field.

Figure 4: Effect of metal thickness on the output electric field resulted of Au/Si3N4 antenna.

Figure 5 shows the impact of increasing the width of the antenna on the output signal. The figure shows that the effect of the change of the width is not as significant. This is because only the dimension along which the incident field is applied will have an effect on the output; while the perpendicular direction will have no effect. In this study, the incident electric field is applied along the length. Therefore, the width should not affect the output. Nevertheless, there is still an increase of about 13% between the smallest and the largest width. The change in the output field is not due to the change in the width dimension, but it is due to the increase of the surface area of the antenna. The increase of the surface area increases of the absorbed power of the incident signal, and this, in turn, increases the output, as shown in the figure.

Figure 5: Effect of width on the output electric field resulted of Au/Si3N4 antenna.

Figure 6: Effect of length of the output electric field resulted of Au/Si3N4 antenna.
The performance of the antenna was simulated with different lengths: 8, 12, 16, 20, and 25 μm. The simulation results are shown in Figure 6. As can be seen from the figure, the peak frequency changes with the change of the length. The peak frequency is found to be, approximately, 4 THz for L= 8 μm, 3 THz for L= 12 μm, 2 THz for L= 16 μm, 1 THz for L= 20 μm. However, for L= 25 μm, the output has no peak. The absence of the peak does not mean it does not exist. The peak exists outside the range of our simulation, which is below 1 THz.

The peak of the output occurs at a fundamental resonant frequency, $f_0$ [27]. This resonant frequency can be obtained from the following equation

$$f_0 = \frac{c}{2\pi L \sqrt{\varepsilon_{\text{eff}}}}$$

(3),

where, $c$ is the speed of light, $L$ is the length of the antenna and $\varepsilon_{\text{eff}}$ is the effective dielectric constant at $f_0$. Because of the periodic nature in the geometry, the resonance of the antenna takes place, not only at the fundamental frequency, but also at the multiples or fractions of the fundamental frequencies [27]. These frequencies are related to the fundamental frequency as $f_0/n$, $n f_0$, where $n$ is an integer. It should be noted that Equation (3) provides an approximate value for the fundamental frequency. But, more importantly, it explains why the resonant frequency changes with the length and why there are multiple peaks in the output.

From Equation (3), for L=16 μm and $\varepsilon_{\text{eff}} = 7$ for Si$_3$N$_4$, $f_0 = 3.5$ THz. This is close to the second peak in Figure 3, which is about 4 THz. The highest peak is at about 2 THz, which is equal to $f_0/2$. Equation (3) shows that the resonant frequency is related to $1/L$. Hence the resonant frequency increases with the decrease of the length. This is clearly shown in Figure 6, where the resonant frequency for L=20 μm is 1 THz, while it increases to 4 THz when the length is decreased to 8 μm. The figure also validates the assertion that the output electric field is affected by the length, since the incident electric field is applied along that dimension.

Antenna made of ITO/Si$_3$N$_4$ substrates were analyzed next. For ITO, the conductivity was taken to be $1.3 \times 10^4$ S/m, and the dielectric constant was taken to be $3.37 + 0.01 j$. Figure 7 shows the effect of the gap size on the output. Similar to the Au antenna, the output decreases as the gap increases, which is directly related to the decrease of the gap capacitance. Figure 8 shows the effect of the gap size on the output. Again, the increase of the thickness increases the conductivity, which in turn, increases the flow of the electrons leading to the increase of the charge accumulation. And this leads to the increase of the output field. The effect of the antenna width is shown in Figure 9. In this case, as the case with the Au antenna, the increase of the output is a result of the increase of the surface area.
As shown in Figure 10, the resonant frequency decreases with the increase of the length, as explained by equation (3). For \( L=25\mu m \), the resonant frequency could not be seen because it is outside the simulation range of the study. This is confirmed from the increase of the output at frequencies below 1 THz.

The behaviors of the Au and ITO antennas are almost identical. The only difference is that the output of a Au antenna is higher than that of an ITO antenna. This can be attributed to the high conductivity of Au compared with ITO, as explained before.

**Conclusion**

We have successfully designed and analyzed two types of antennas using COMSOL: Au/Si\(_3\)N\(_4\) and ITO/Si\(_3\)N\(_4\). The study shows that Au antennas can provide higher output, and ITO antennas can be integrated with both electrical and optical devices. The study shows also that the output electric field is affected by the size of the antenna gap, the thickness of the metal layer, the width, and the length of the antenna. From this study, the optimum design for a desired application can be obtained. The length of the antenna affects the resonant frequency, where the peak frequency decreases as the length increases. Integrating antennas with different lengths allows for building wide band THz detectors. Au and ITO antennas can be easily integrated with microelectronic technology, due to the compatibility of the materials used. Comparing SiO\(_2\) bow-tie antenna to Si\(_3\)N\(_4\) antenna, one can realize that the resonant frequency for SiO\(_2\) antennas are higher, since its dielectric constant is lower. The second is the power output for SiO\(_2\) antennas is higher than the output of Si\(_3\)N\(_4\) antennas. However, using arrays can provide the required output power for any of them.

**References**


