Development of new photoconductive antennas for generation and detection of terahertz radiation using a high-precision ink-jet printer

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INTRODUCTION

The objective of this joint research is exploring new photoconductive antennas (PCAs) or metallic structures, for efficient THz emission and detection using cost-effective and easy-to-use fabrication techniques. One promising technique is the use of a high-precision ink-jet printer, which is available at Prof. Hangyo’s group in ILE. The high-precision ink-jet printer can fabricate metallic patterns, with micrometer resolution, on semiconductor substrates by using metallic ink directly or resin ink and spin-coating technique.

To examine this technique, we initially fabricated a simple metal-hole structure on a semiconductor substrate in the last fiscal year (FY2011). A gold film with holes (~ 10 μm in diameter) on a semi-insulating (SI) - GaAs substrate was fabricated using a high-resolution ink-jet printer. A two times enhancement was observed compared to the bare surface. Moreover, this Au metal-hole was compared with an Al metal hole-array structure (250-μm hole diameter and 400 μm periodicity in a square array configuration) made with a standard photo-lithographic technique and results showed that the small Au metal-hole is a better design even when using a simple fabrication technique (see the report last year for the detail).

In this fiscal year, we explored a different direction in making use of the high-resolution ink-jet printer for fabrication of new types of PCAs, that is, multi-contact PCAs. Multi-contact PCAs can be used as polarization controllable THz emitters or polarization resolving THz detectors. In previous works, we have demonstrated a four-contact PCA as a polarization controllable THz emitter [1] and a three-contact PCA as a polarization resolving THz detector [2]. However, the antenna designs were not optimized since the parametrical optimization by making a variety of multi-contact antennas is costly and time-consuming if we use the standard photo-lithographic techniques.

We have fabricated a four-contact PCA similar to that reported in [1] as the trial design and planned to evaluate its performance as a polarization controllable THz emitter and polarization resolving THz detector.

FOUR-CONTACT ANTENNA

Figure 1 shows the microscopic optical image of the four-contact PCA fabricated by the high-precision ink-jet printer on an SI-GaAs substrate. Only the rim parts of the metallic contacts were drawn by the high-precision ink-jet printer since the electric field distribution is determined by the charge distribution on the rim parts of the contacts. When we apply a positive (or negative) bias voltage to two adjacent contacts, the electric field in the center part of the photoconductive gap is directed to +45° or -45° to the vertical axis of Fig. 1. By shifting the bias to the next two-adjacent contacts we can rotate the electric bias field in the photoconductive gap by 90°, and accordingly the polarization axis of the THz radiation emitted from the PCA.

When we use this four-contact antenna as the photoconductive detector, we measure two current signals, $I_1$ and $I_2$, from the orthogonal contact pairs as depicted in Fig. 2. There are six current components (see Fig. 2(a)) which contribute to the photoconductive signal currents to be measured. It is difficult to determine the photoconductive response of each component. However, if we assume a linear response of the PCA to an orthogonal set of THz fields, for example, x and y axis components ($E_x$ and $E_y$), the response of the PCA to an arbitrary THz field is given by the following equation, even if we don’t know the photoconductive response of each contact pair.

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix}
= A
\begin{pmatrix}
r_{11} & r_{12} \\
r_{21} & r_{22}
\end{pmatrix}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
\]

(1)
Fig. 2. (a) The center part of the 4-contact PCA, and (b) The equivalent circuit of the 4-contact PCA.

Here, $I_1$ and $I_2$ is the photoconductive signal current induced by the THz field $(E_x, E_y)$ in the equivalent circuit shown in Fig.2(b). “$A$” is a scaling factor depending on the sensitivity of the antenna and the probe beam intensity. The $r_{ij}$ is the matrix component describing the PCA response to THz fields and determined by measuring the photoconductive response of the antenna to an orthogonal set of THz fields with equal amplitude ($|E_x| = E_0$ and $|E_y| = E_0$). By using the inverse matrix of the PCA response, $\beta_{ij} = r_{ij}^{-1}$, we can determine the polarization of the THz wave incident on the PCA detector from the measured photoconductive THz current $I_1$ and $I_2$:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = B \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix}$$

Here $B = 1/A$.

CONCLUSION

We have demonstrated fabrication of a four-contact PCA by the high-precision ink-jet printer. The evaluation of the four-contact PCA as the polarization controllable THz emitter and polarization resolving THz detector is now ongoing. We hope we can report the properties of the four-contact PCA soon. We believe the high-precision ink-jet printer is very useful for development of complicated PCA structures, not only four-contact PCAs but also much more complicated antenna structures.

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