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Non-contact resistance measurement of transparent electrodes deposited on flexible display substrates under repetitive bending test by terahertz time domain spectroscopy

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ABSTRACT

The objective of this study is to put forward a new non-contact resistance measurement method for repeating bending tests of transparent electrodes deposited on flexible display substrates. The study utilizes a terahertz time domain spectroscopy (THz-TDS) method to measure electrical properties of flexible polyethylene terephthalate/indium tin oxide samples up to 20,000 bending times. In addition, this study utilizes THz-TDS method to measure electrical characteristics of flexible substrates with hard-coat films. Accordingly, the percentage errors of measured sheet resistances based on THz-TDS method are less than or equal to 5.5% for comparison with a contact type four-point probe method or our previously reported flexible characteristic inspection system method. The values show a reasonable agreement with contact-mode sheet resistance measurements. Therefore, the electrical properties of thin films are measured offline or online easily by using this method.

1. Introduction

Thin-film devices fabricated with nanotechnology have increased recently and are widely used in different areas, such as integrated circuits, flat panel displays (FPD), optical coatings, photovoltaic and other cutting-edge electromechanical systems. Hard FPD products do not satisfy people who demand a comfortable and convenient lifestyle. Flexible displays, which are thin and flexible, shock-resistant, and not limited by the occasion or space, will be used as next generation monitors and replace newspapers and books in daily life in the form of electronic papers and electronic books. The main difference between hard FPDs and flexible displays is that as substrate materials plastic sheets are utilized in flexible displays rather than glasses in hard FPDs [1–6]. For flexible electronics, transparent conducting materials are deposited on plastic substrates [7–14]. The excellent electrical characteristics of thin film material for semiconductor fabrication is used for achieving the proper electrical design requirements. At present, a relatively mature standard method for measuring conductivity of the materials is the four-point probe contact method [15]. However, the thinner flexible samples may be pierced during the measurement, and hence increases the measurement uncertainty. In addition, mass electrical measurements require a lot of time to prevent pierced damage by using the four-point probe method. According to the literature [16–18], terahertz time domain spectroscopy (THz-TDS) has emerged as a main spectroscopic modality to fill the frequency range between a few hundred gigahertz to a few terahertz. THz-TDS is utilized to explore the material characteristics of hard-type samples by non-contact mode measurement. Therefore, this study created a new non-contact and non-destructive resistance measurement method for repeating bending tests of flexible polyethylene terephthalate (PET)/Indium tin oxide (ITO) samples by using a terahertz time domain spectroscopy (THz-TDS). A flexible characteristics inspection system (FCIS) [19,20] with a THz-TDS is utilized to measure electrical properties of flexible PET/ITO samples up to 20,000 bending times. Additionally, this study utilizes THz-TDS method to measure electrical characteristics of flexible substrates with hard-coat films. To provide a reference standard for non-contact resistance measurement, this study utilizes a contact-mode four-point probe measurement method to measure electrical characteristics of flexible substrates by a careful contact measurement.

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2. Principle of THz-TDS

Random noise in measurement can be reduced by averaging a series of signals obtained from multiple repeated measurements. The averaging is effective in the time domain, but not in the frequency domain [16]. THz-TDS is based on the direct time-domain sampling with an ultrafast-laser pump/probe configuration. Its broadband measurement capability and strong immunity to background noise facilitate observation of terahertz–material interactions, which are attractive to researchers in a wide range of fundamental disciplines. To measure electrical properties of transparent electrodes deposited on flexible substrates by a non-contact method, the transmission type THz-TDS system based on the general photoconductive antenna detection is utilized, as shown in Fig. 1. Transmitted THz electric field depends on the optoelectronic characteristics of the sample [17]. Additionally, the Fourier transforms of the THz waveform based on the time dependent fields are related to the conductivity of the films by the thin film equation [17,18]. To obtain electrical properties of thin film on the sample, relationship of transmission coefficient $T(\omega)$ and conductivity $\sigma(\omega)$ can be derived as,

$$T(\omega) = \frac{E_{film+subst}(\omega)}{E_{subst}(\omega)} = \frac{1+n}{1+n+Z_0\sigma(\omega)d}, \quad (1)$$

where $E_{film+subst}(\omega)$ and $E_{subst}(\omega)$ are the electric fields of the THz pulse transmitted through the thin film sample, and through the uncoated area of the substrate, respectively. In Eq. (1), assume that the conductivity of the uncoated area of the substrate is zero. $\sigma(\omega)$ is the conductivity of the thin film on the substrate. Z_0 is the free space impedance, n is the refractive index of the substrate, and d is the thickness of the film.

Solving Eq. (1) gives

$$\sigma(\omega) = \frac{(1+n)(1-T(\omega))}{T(\omega)Z_0 d} \quad (2)$$

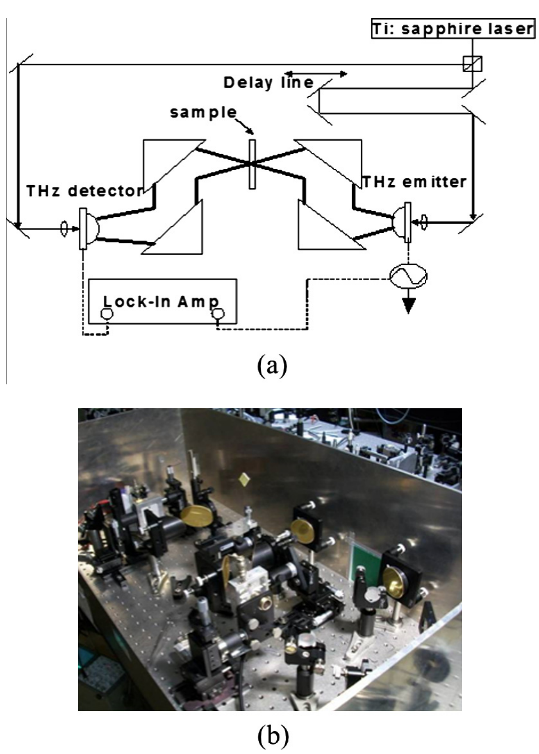

Fig. 1. (a) Schematic diagram and (b) photo of THz time-domain spectroscopy system.

In theory, the resistivity is the reciprocal of the conductivity. The sheet resistance R_s is generally denoted as ρ/d, where ρ is the resistivity of the thin film [21]. Therefore, the sheet resistance of the thin film on the substrate is obtained as

$$R_s = \frac{\rho}{d} = \frac{1}{\sigma(\omega)d} = \frac{T(\omega)Z_0}{(1+n)(1-T(\omega))} \quad (3)$$

For the calculation this study assumes a purely real and frequency-independent bulk conductivity, $\sigma(\omega) = \sigma_{bulk}$, which is a good approximation for bulk materials at low terahertz frequencies [18]. In Eq. (3), the refractive index of the substrate in the THz regime stays constant, and transmission coefficient at low terahertz frequency is independent of the frequency due to frequency-independent bulk conductivity. Therefore, a transmission type THz-TDS method can be used to measure the sheet resistance of the transparent thin film on the substrate depended on different materials and structures by the refractive index of the substrate and transmission coefficient.

3. Sample preparation

In this study, the flexible display substrate is a commercial ITO thin film with the thickness of ~50 nm, deposited on a 4.8 × 7.5 cm PET substrate (OCTM100) with the thickness of 125 μm from CPFilms Inc. To measure transmission coefficient of PET/ITO sample, the half of the sample is etched with a solution of HCl:H_2O (1:1) for exposing the PET substrate, as shown in Fig. 2.

4. Experimental method

From Fig. 1, THz radiation is generated from laser excitation and a voltage-biased photoconductive antenna with a gap size of 5 μm. The excitation and sampling laser source is the mode-locked Ti: sapphire laser with the pulse width, the center wavelength and the average power of around 100 fs, 840 nm and 50 mW, respectively. The THz radiation is guided and focused on the sample by a pair of gold-coated off-axis parabolic mirrors. It is then focused on the other similar photoconductive antenna detector by another pair of the gold-plated off-axis parabolic mirrors. It is equivalent to imposing a THz frequency voltage on the detector, resulting in a photocurrent. The detected current signal is proportional to the THz electric field, and the THz radiation waveform can be read out through the lock-in amplifier by the mechanical movement induced optical delay between the excitation and detection laser. According to the half of the sample in Fig. 2, the transmitted THz radiation waveform of PET and PET/ITO samples with a 2 mm measurement spot are obtained by the transmission type THz-TDS measurement structure. In this study, Z_0 is 376.73 Ω [22], n is 1.65 [23], and d is 50 nm for the free space impedance, the refractive index of the PET substrate, and the thickness of the ITO film,

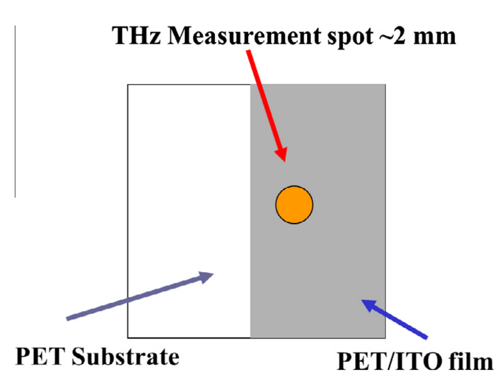

Fig. 2. Configuration of the testing PET/ITO sample.