

# Joining aluminum sheets with conductive ceramic films by ultrasonic nanowelding



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## ABSTRACT

Directly joining metal electrodes with ceramic films is desired for many applications in electronic manufacture. In this work, ultrasonic nanowelding was used successfully to join aluminum (Al) sheet onto indium tin oxide (ITO) and aluminum-doped ZnO (AZO) ceramic thin films. The results show that the contact resistance of the nanowelded bonds is as low as that of the conventional silver paste joints, and the contact strength is enhanced dramatically after nanowelding. Compared with Al–ITO joint, the contact strength between Al and AZO is a little higher because of the different roughness at the joint interface. From the rupture interface of the joint zone after stress–strain measurement, domains of Al atoms have been observed, which suggests that a reliable bonding is formed between Al and the ceramic films.

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## 1. Introduction

Ceramics are preferred in a wide range of engineering and electronic applications due to their outstanding physical and chemical properties such as high thermal stability and corrosion resistance, high compression modulus and intensity, excellent thermal and electrical resistivity compared to other materials [1,2]. Ceramic films, especially conductive ceramic films, are widely used as the electrodes of thin film solar cells and flat panel display [3,4]. It is very necessary to join ceramic films with metal components for many applications in electronic manufacture. However, it is a big challenge to achieve good ceramic–metal bonding due to the difference in thermal expansion and chemical reactivity between the two types of materials [5]. The difference in thermal expansion leads to residual stresses; while a difference in chemical reactivity results in a brittle deformation at the interface, resulting in the degradation of the bonding strength between ceramic films and metal sheets. Several methods such as mechanical fasteners, adhesive bonding and solid-phase bonding have been developed to bond metal with ceramic films. Among these methods, solid-phase bonding is the most effective way to produce reliable joints between metal and ceramics [6,7]. Solid-phase bonding could be realized by brazing [8], friction welding [9], explosive welding [10], and diffusion bonding [11]. Wei et al.

ever reported ultrasonic-assisted brazing of sapphire with Al alloys as a filler metal [12]. However, the wettability of the filler metal/substrate system is poor for many other ceramics. Gambaro et al. found excellent wettability of transparent YAG ( $\text{Y}_3\text{Al}_5\text{O}_{12}$ ) with help of molten Ag–Cu–Ti alloys [13]; however, high temperature in brazing significantly limits its applications. Recently, ultrasonic welding has shown a promising application in joining metal with ceramic at room temperature [14,15]. Ishikuro et al. reported ultrasonic welding of thin ceramics and metal using Al alloys as a binder layer by vapor deposition [16]. However, the big amplitude of the horn tip (30  $\mu\text{m}$ ) tends to exfoliate the inset layer, which is not suitable for welding nanoscaled ceramic thin films. Furthermore, the inset layer could exert destructive effects on the welded electronic devices.

Ultrasonic nanowelding has been developed to create reliable contacts between one-dimensional nanomaterials and metals [17,18]. The bonds produced by this method have demonstrated good long-term stability and mechanical strength by applying a force vibrating at ultrasonic frequency. In this paper, two-dimensional nanomaterials such as indium tin oxide (ITO) and Al-doped ZnO (AZO) ceramic thin films were welded with metals by high-frequency ultrasonic energy. The frequency is so high that the vibration displacement is at the nanoscale, which is critical to protect the welded nanomaterials. Al sheets were directly bonded onto ITO and AZO ceramic thin films by ultrasonic nanowelding, and the conductive and mechanical properties of the welded joints were investigated.

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## 2. Experimental

Al sheets with purity of 99.9 percent and size of  $5 \times 5 \times 0.1$  mm ( $L \times W \times T$ ) were used in this study. ITO and AZO thin films were deposited on glass substrates by magnetron sputtering. The thickness of the ITO and AZO thin films was about 250 nm. Fig. 1 shows an outline of the ultrasonic nanowelding with ultrasonic vibration frequency of 60 kHz. The pyramid-like protuberances are created on the surface of the cemented carbide welding head for preventing slippage between the head and samples. A welding force was applied to press the welding head against the Al sheet and ceramic thin films.

Atomic force microscopy (AFM, Veeco Dimension 3100) were used to observe the surface morphology of the as-deposited ceramic films. In order to investigate the conductive properties of the bonding joint, experimental circuit was designed and shown in Fig. 2a. Conductance measurements were performed in precision semiconductor analyzer (Agilent 4156C) using Ag paste as the other electrode (10 mm away from each other). For comparison, the same size of Ag paste was used as a substitute for the Al sheet in the unwelded samples.

The bonding strength was investigated by dynamic mechanical analyzer (DMA, TA Q800), and the schematic of the measurement is shown in Fig. 2b. Two rigid sticks were symmetrically spliced on welded Al and back glass by epoxy. The morphology of the fracture zone was observed using scanning electron microscopy (SEM, Zeiss Ultra55) at an operating voltage of 5 kV.

## 3. Results and discussion

In Fig. 3, two micrographs of AFM show the surface grain structures of the as-deposited ITO and AZO thin films. Both of the films show many crystal grains on the surfaces. However, ITO films show a relatively bigger grain size as well as a smoother surface. The root-mean-square roughnesses for ITO and AZO films are 3.6 and 5.6 nm, respectively.

The  $I$ - $V$  characteristics of the ITO and AZO thin films with and without welded Al sheets are shown in Fig. 4. Typical linear behaviors are observed for all of the samples. From Fig. 4a, it can be seen that the two-terminal resistance between the two Ag pastes on the surface of ITO films is  $27.5 \Omega$ , while the resistance is  $28.4 \Omega$  between Ag and welded Al sheet. The increase of the value could be attributed to the effect of the contact resistance between welded Al and ITO films. The 3.3 percent of the variance in resistance is tolerated in metal–ceramic welding, which suggests a good joint between Al sheets and ITO films. In the case of AZO films, as shown in Fig. 4b, the resistances are 10.8 and  $11.1 \Omega$  in welded and non-welded Al sheets, respectively. The contact resistance is increased by 2.7 percent, which indicates that an effective electrical

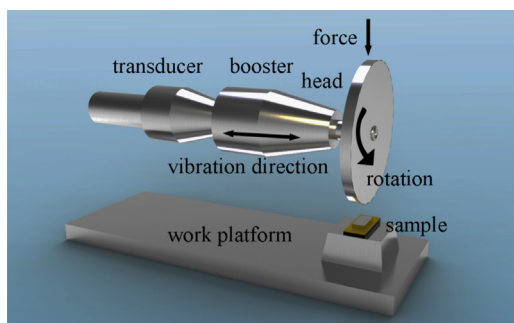


Fig. 1. Schematic of the ultrasonic nanowelding.

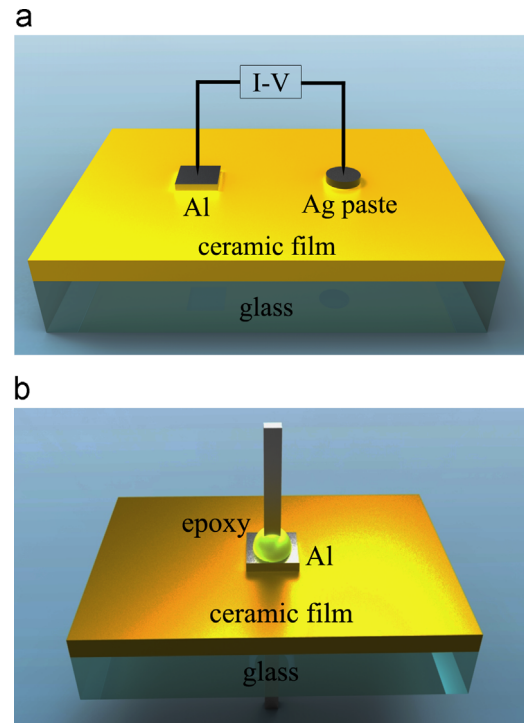


Fig. 2. Schematic of the conductance (a) and bonding strength (b) measurements for the welded Al sheet on ceramic films.

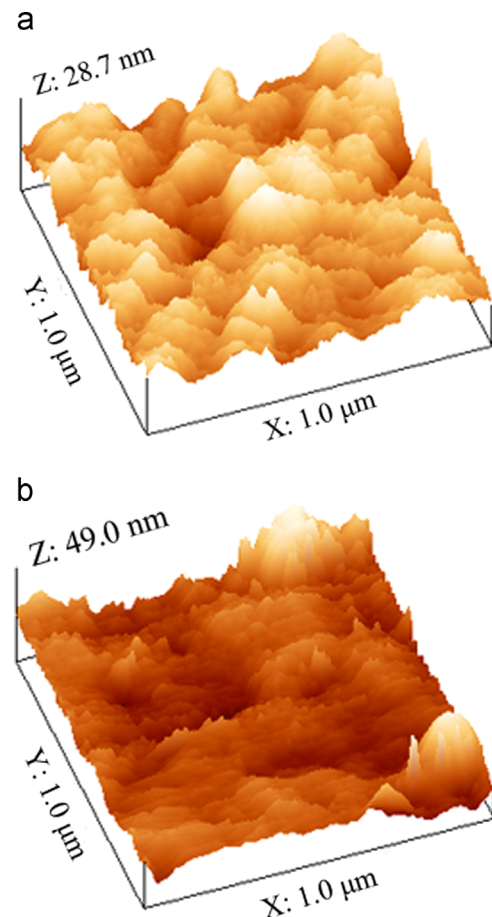


Fig. 3. AFM images of as-deposited ITO (a) and AZO (b) films.

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