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Disk-type piezoelectric transformer of a $Na_{0.5}K_{0.5}NbO_3$–$CuNb_2O_6$ lead-free ceramic for driving T5 fluorescent lamp

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A B S T R A C T

Lead-free $(Na_{0.5}K_{0.5})NbO_3$ (NKN) ceramics doped with 1 mol% $CuNb_2O_6$ (CN) ceramics were prepared using the conventional mixed oxide method, with a sintering temperature of 1075 °C. Microstructural analyses of the NKN–01CN ceramics were carried out and compared, using X-ray diffraction (XRD). NKN–01CN ceramics sintered at 1075 °C not only exhibited excellent 'hard' piezoelectric properties of $k_p = 40\%$, $k_t = 45\%$, $k_{33} = 57\%$, a ferroelectric property of $E_c = 23$ kV/cm, and an extraordinarily high mechanical quality factor (Q_m) of 1933 but also showed excellent stability with temperature (TCF = −154 ppm/°C). The piezoelectric transformer was simplified, using an equivalent circuit, and analyzed, using MATLAB; the simulation data agreed well with the experimental results. An efficiency of 95.7% was achieved for the NKN–01CN piezoelectric transformer with load resistance of 20 kΩ. An 8 W T5 fluorescent lamp was successfully driven by the NKN–01CN piezoelectric transformer.

1. Introduction

Piezoelectric transformer (PT), which combines piezoelectric actuators and piezoelectric transducers, are good substitutes for traditional magnetic transformers. Piezoelectric transformers have many advantages, including their high voltage gain, high power density, high electromechanical efficiency and small size. Since the invention of the first PT was invented by Rosen [1], various types of PT have been developed, such as the disk-type, ring-type and multi-layer [2–4]. Recently, piezoelectric transformers have been used in many applications, such as AC/DC converters, electronic ballasts for fluorescent lamps and inverters for driving CCFL (LCD backlights) [5,6].

Lead zirconate titanate (PZT) and PZT-based multi-component piezoelectric ceramics with a perovskite structure have been widely used in actuators, sensors, resonators, transducers and transformers because of their excellent piezoelectric and electrical properties [7,8]. However, the high volatilization of PbO, a main component of PZT ceramics, limits the use of these materials, because it contaminates the environment and harms human health, due to its toxicity. Lead-free materials have attracted increasing attention, as replacements for PZT-based piezoelectric ceramics. Sodium potassium niobate ($(Na_{0.5}K_{0.5})NbO_3$, NKN) ceramic is considered to be a good candidate for lead-free piezoelectric ceramics because of its strong piezoelectricity and ferroelectricity [9]. However, it is very difficult to synthesize ceramics with a dense microstructure, so many researchers have reported the addition of (Li, Sb, Ta) compounds to NKN ceramics, to improve the densification and enhance the piezoelectric properties of the samples [10–15]. In addition, CuO, or CuO compounds serve as good dopants for enhancing the Q_m value of NKN ceramics because of the formation of oxygen vacancies. A high Q_m is required for actuator and high-power applications, such as PT. Therefore, the microstructure, crystal and electrical properties of NKN ceramics, with CuO or CuO compounds have been widely investigated [16–20].

In this work, a small amount of Cu compound ($CuNb_2O_6$, CN) was selected as a dopant for NKN ceramics, to replace CuO. The results show that the CN-doped NKN specimens sintered at 1075 °C, display excellent 'hard' piezoelectric properties and ferroelectric properties. The mechanical quality factor (Q_m) of NKN ceramics with CN additive is extraordinarily high. CN improves the ability to be sintered and the electrical properties of NKN ceramics. The addition of a small amount of CN improves both the ability to be sintered and Q_m of NKN ceramics.

2. Experimental procedure

In a previous study [21], the authors found that $Na_{0.5}K_{0.5}NbO_3$ ceramics doped with 1 mol% $CuNb_2O_6$ have excellent piezoelectric properties. The samples of

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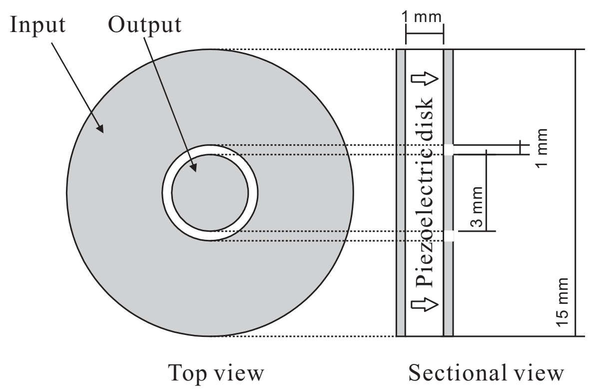

Fig. 1. Structure of a disk-type piezoelectric transformer.

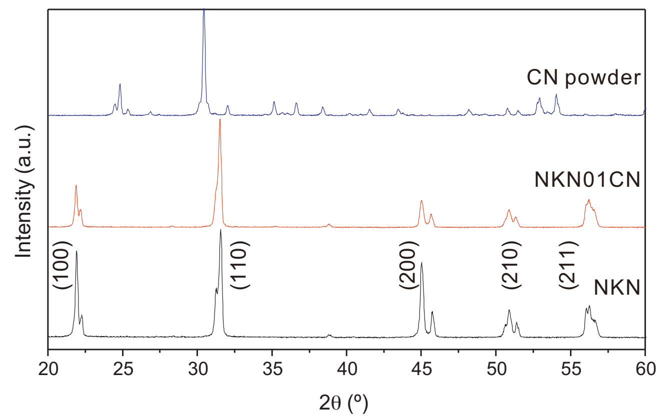

Fig. 3. XRD patterns of the CN powder, NKN–01CN ceramics, and NKN ceramics sintered at 1075 °C, for 3 h.

starting materials of $Na_{0.5}K_{0.5}NbO_3$–$x$$CuNb_2O_6$ (NKN–xCN, for x = 0, and 1 mol%) processed using a conventional mixed-oxide method were pure reagent-grade Na_2CO_3 (SHOWA, 99.5%), K_2CO_3 (SHOWA, 99.5%), Nb_2O_5 (SHOWA, 99.5%) and CuO (SHOWA, 99.5%) powders. $Na_{0.5}K_{0.5}NbO_3$ (NKN) and $CuNb_2O_6$ (CN) were weighed in the desired compositions, respectively. The starting materials were individually transferred to a 100-mm-diameter cylindrical plastic jar, partially filled with 10 mm diameter ZrO_2 grinding balls. Sufficient ethanol (99.5%) was added to cover the powders. Ball milling was performed for 24 h, followed by drying at 130 °C, and then grinding, using an alumina mortar and pestle, to break up large agglomerates formed during drying. The stoichiometric NKN and CN powders were first synthesized, using a solid-state reaction method, at 850 °C, for 5 h and 900 °C, for 5 h, respectively. After the calcination, NKN and CN powders were weighed according to the formula of NKN–xCN and ball milled for 24 h. These powders, milled with 5 wt.% PVA aqueous solution, were uni-axially pressed into a disk of 18-mm diameter, at a pressure of 25 kg/cm^2 and subsequently sintered in air at 1075 °C, for 3 h.

Bulk densities were measured using the Archimedes method, with distilled water as the medium. The microstructure was observed using field emission scanning electron microscopy (FESEM), with a Hitachi S-4100 microscope. The crystallographic study was confirmed by X-ray diffraction (XRD) using Cu K_α (λ = 0.154 nm) radiation with a Siemens D-5000 diffractometer, operated at 40 kV and 40 mA. The dielectric and piezoelectric properties were measured with an HP 4294A precision impedance analyzer. To measure the electrical properties, silver paste was painted on both sides of the samples, to form electrodes; the samples were subsequently fired at 150 °C, for 20 min. Then, the samples were poled, in silicone oil, in a 30 kV/cm DC field at 150 °C for 30 min. The electromechanical coupling factor of thickness (k_t) and planar (k_p) mode was calculated using the resonance–antiresonance method. The piezoelectric coefficient, d_{33}, was measured using a Wide-Range d_{33} Tester 90-2030 (APC International, Ltd.). The coercive electric field (E_c) and the remnant polarization (P_r) were obtained in a 50 kV/cm 60 Hz AC field, using a modified Sawyer–Tower circuit [22]. In order to prevent arcing, the samples were submerged in 150 °C silicon oil.

In this experiment, an NKN–01CN piezoelectric disk of a 15-mm outer diameter, a 3-mm inner diameter and a 1-mm thickness was designed and evaluated as a disk-shaped PT. As shown in Fig. 1, the piezoelectric disk has silver electrodes. The width of the gap circle is 1-mm and the poling direction is the thickness direction. The characteristics of the transformer, under a variable load resistance, were investigated using the experiment setup shown in Fig. 2. The transformer was driven by a MOTECH FG-708S function generator and an NF BA4825 high speed bipolar amplifier. The voltage, current and power, at the input and output, were measured using a Tektronix TCP A300 current probe and a DPO 2024 digital phosphor oscilloscope.

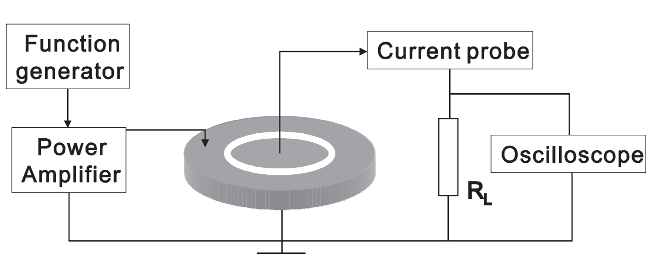

Fig. 2. Experimental setup for measurement of the characteristics of the piezoelectric transformer.

3. Results and discussion

The XRD patterns of the CN-modified NKN piezoelectric ceramics, sintered at 1075 °C, and CN powder are shown in Fig. 3. A homogeneous, pure NKN phase was well developed for 1 mol% CN additive. The main identified phase matches orthorhombic NKN with space group A*mm*2, at room temperature [23]. The results reveal that the orthorhombic perovskite structure is preserved (JCPDS card No. 32-0822). None of the phases ascribed to $CuNb_2O_6$ were detected. Fig. 4 shows the SEM images of NKN and NKN–01CN ceramics, sintered at 1075 °C. Both of the ceramics have a dense structure and the grains are generally rectangular in shape. For the NKN ceramic, the grains arrange in size from 1 to 2 μm. After

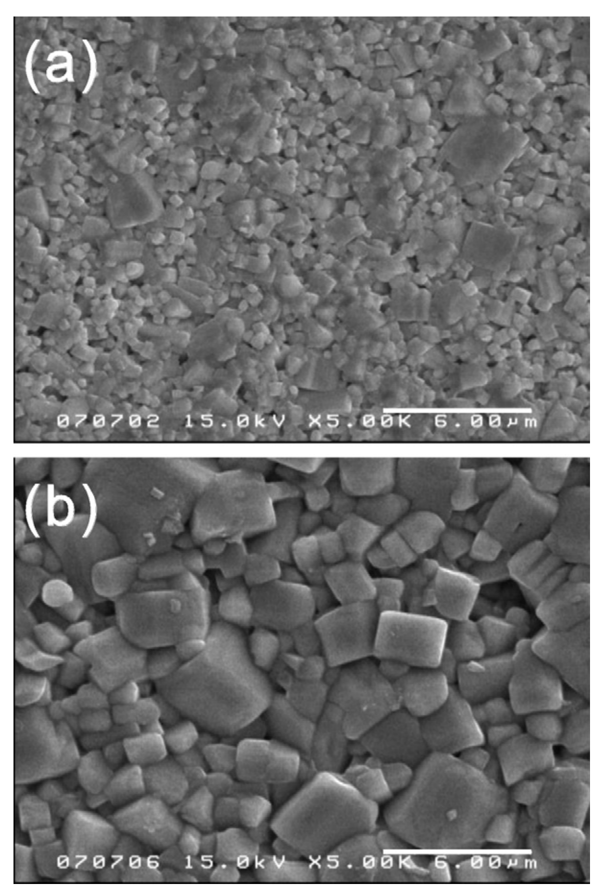

Fig. 4. SEM images of (a) NKN and (b) NKN–01CN ceramics, sintered at 1075 °C.