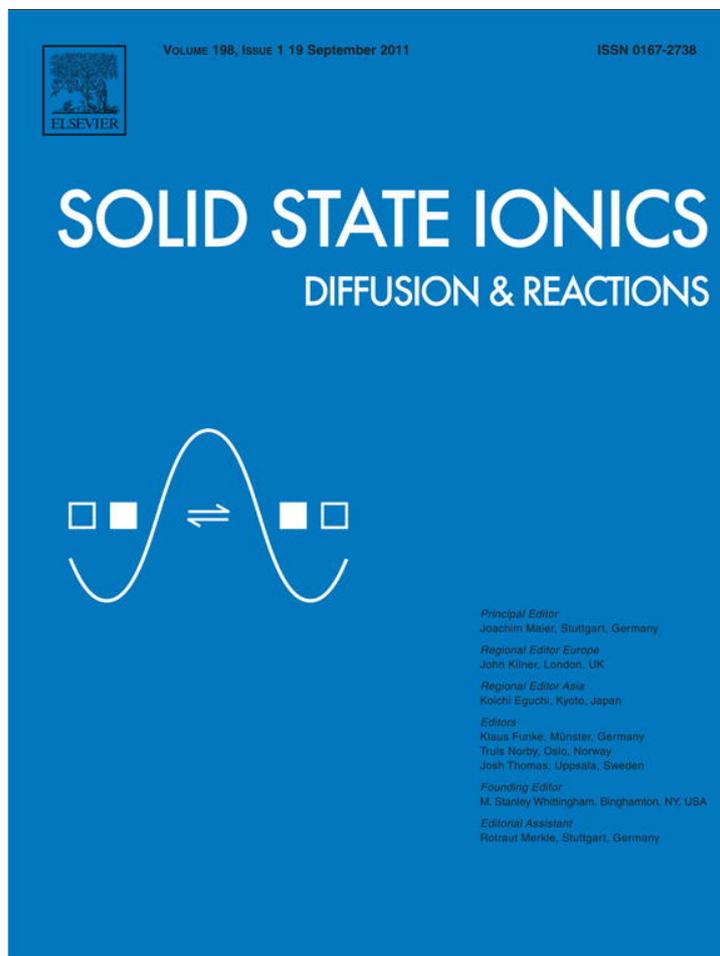


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## All solid state ion-conducting cesium source for atomic clocks

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### ARTICLE INFO

#### Article history:

Received 15 September 2010

Received in revised form 4 July 2011

Accepted 12 July 2011

Available online 11 August 2011

#### Keywords:

Alkali glass ionic conductor

Cesium source

Atomic clock

### ABSTRACT

Cesium containing glass with solid metal electrodes was used as a Cs atom source in a high vacuum system. A silver anode provides an injection source of highly mobile ions which sweep Cs to the cathode surface, from which they evaporate into the vacuum. Cathode metallization with finger patterns was used leaving bare glass for Cs evaporation. Laser absorption measurements show Cs vapor generation synchronous with an applied DC voltage.

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### 1. Introduction

Multiple methods are known for dispensing small quantities of alkali vapors from a solid source. Use of solid or liquid Cs is problematic due to extreme reactivity with air and water. Some commercially available sources contain alkali metal salts plus a reducing agent [1] which react to liberate alkali. Other sources contain alkali intermetallic compounds [2] which evolve alkali when heated. Both types of commercial sources use large electrical currents to heat the source to a reaction temperature and have typical dispensing capacities of several milligrams. For some purposes, e.g. populating magneto-optical traps (MOTs), only a few million atoms are required, and a source with smaller capacity may be sufficient.

Ionic conduction in glass has also been studied as a method for sourcing Na [3], K and Cs. Re-entrant glass thimbles [4] made from a Cs-containing glass were used to produce Cs using a molten salt anode, with a tungsten filament cathode provided electrons to neutralize ions at the glass surface. The Cs emitted at the cathode could not be replaced using molten Cs salts at the anode. More recently, this technique was used as a source of Cs in a glass to silicon anodically bonded cell [5]. In this work, a molten salt anode was used as a source of Na ions injected into the glass to replace migrating Cs ions.

In these previous studies, a molten salt anode was used as a source of ions, and the alkali containing glass was made part of the vacuum system wall. The molten salt anode requires high temperatures to operate, and building the alkali-containing glass into the vessel wall

precludes the use of these sources completely inside a vacuum chamber.

In other previous work, a Cs ion beam source was constructed using a solid Cs-Mordenite (synthetic zeolite) ceramic operated at 800–1200 °C [7]. This source used a sputtered porous tungsten cathode and a platinum (non ion injecting) anode.

This study introduces an all solid state alkali source comprising alkali-containing glass, a continuous Ag anode and a metal cathode with finger patterns partially covering the alkali-emitting surface. Ag and Cu form non-blocking electrodes whose ions have high mobility in glass [6] and do not react with metallic Cs [8]. Efficient injection of Ag ions at the anode prevents a large voltage buildup in an ion-depleted glass layer and undesirable oxygen evolution. No molten salt anode is required, and the source can be completely contained within the vacuum system. Alkali production can be controlled via the applied current or voltage. Operation is demonstrated at greatly reduced temperature compared to previous solid state ion sources.

### 2. Experimental

Cesium borate glass containing 25 mol% Cs<sub>2</sub>O was made at Coe College. Appropriate amounts of cesium carbonate and boric acid were melted in a crucible at 1000 °C for 15 min, then cooled in air and weighed to determine weight loss. The glass was reheated twice more to 1000 °C, then poured into a mold heated to 375 °C and placed into an annealing furnace at 375 °C for 1 day, then lowered to 50 °C in 3 h.

The glass coupon was 25 mm diameter and 4–6 mm thick. This was diced into strips 4–6 mm wide of varying length, and 1 mm thick. These strips were taped to an Invar shadow mask, through which Ti/

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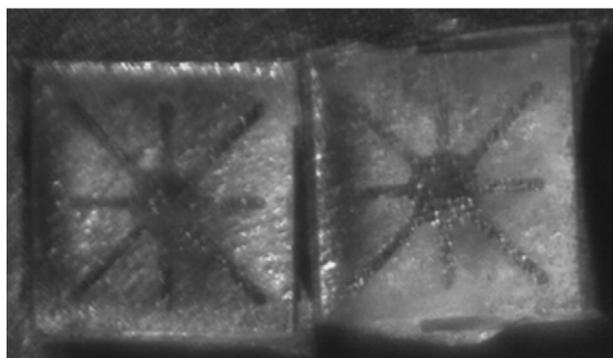


Fig. 1. (3 mm)<sup>2</sup> × 1 mm thick Cs-borate glass squares with shadow masked cathodes. All data were collected using this star pattern cathode.

Cu cathodes (200 nm/2 μm) were evaporated. The glass was then flipped and Ag was evaporated on the entire back surface of the glass. The strips were then diced into 3 mm squares (Fig. 1). Because the glass is very soluble in water, all processing except the initial dicing was performed dry.

The Cs glass squares were tested on square ceramic plates (Al<sub>2</sub>O<sub>3</sub> or ZrO<sub>2</sub>) using a steel wire spring to both hold down the sample and make contact to the cathode metallization (Fig. 2). This ceramic plate was in turn clamped to a vacuum-compatible (19 mm)<sup>2</sup> ceramic heater (Watlow Ultramic) with built in thermocouple. Due to the ceramic substrate and two contacting gaps, the temperature of the Cs glass is estimated to be ~10 °C cooler than that measured at the heater. Heater temperature was limited to 175 °C to avoid melting the solder connections to the ceramic substrate.

Cs generation experiments were performed in a stainless steel vacuum chamber pumped to a base pressure of 4 × 10<sup>-8</sup> mbar after bakeout.

Cs vapor was measured by laser absorption (Fig. 3). A beam from a Toptica DL-Pro laser with frequency scan module was passed approximately 1 mm above the glass sample. The scan module was used to dither the laser frequency and was set to scan across the cesium D2 line at a rate of 10 Hz. A Cs vapor cell was used as a reference signal for the laser frequency. The laser signal detected by a photodiode was sent to an SR850 lock-in amplifier, using the scan rate signal from the laser scan module as a reference. The lock-in was set to extract the second harmonic of the absorption signal with a 10 s time constant and a sampling rate of 2 Hz.

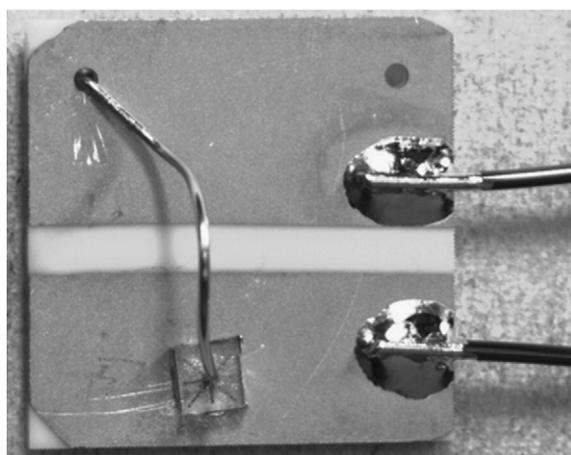


Fig. 2. Cs glass source (3 mm)<sup>2</sup> on an alumina board with spring wire contact/hold-down.

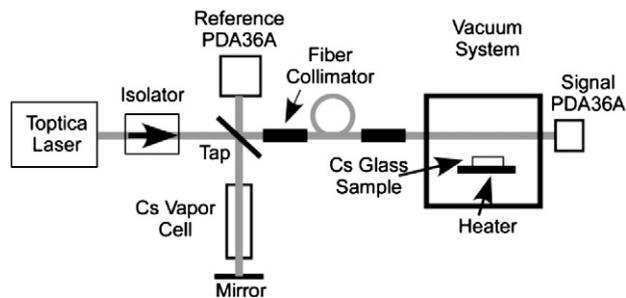


Fig. 3. Laser measurement system sensing Cs vapor from solid state source.

### 3. Results

Fig. 4 shows current voltage (I–V) measurements made between 100 °C and 170 °C (heater set-point). After each voltage step, current transients were allowed to decay for either 30 s or 1 min before collecting data. Large positive current transients followed positive voltage steps, and large negative transients followed negative voltage steps. Current follows a square law, (Fig. 5) indicative of space charge limited conduction.

To enhance surface conduction between the cathode fingers, a film of Ti/Au (3 nm/5.5 nm) was evaporated over the Ti/Cu cathode star pattern on some samples. This metal film can supply electrons to neutralize the Cs ion current at the cathode surface, yet is thin enough that Cs could pass through holes in the film. Au forms an intermetallic compound with Cs, which could also act as a source of Cs vapor. A sample which was measured before and after addition of the thin conducting film saw a 2.5-fold increase in current flow. The Cs vapor signal from this source is shown in Fig. 6, with a drive voltage of 1200 V turned on and off 5 times. The heater temperature was set to 175 °C.

### 4. Discussion

The Cs signal from the glass source was compared to a commercial SAES source, (part number CS/NF/3.9/12 FT10) operated at 3.4 amps. The optical signal from the Cs glass with 1 kV applied and heater at 170 °C was about 20× smaller than that from the SAES source, which produces approximately 1 μg/min [1]. A very rough estimate of current efficiency is obtained by comparing the current flow (0.8 μA or 5 × 10<sup>12</sup> electrons/s) through the glass with the estimated Cs production (50 ng/min, or 3.8 × 10<sup>12</sup> atoms/s) yielding 76%.

Total capacity of the source can be estimated by the concentration of Cs in the glass and the volume of Cs containing glass. For a 3 mm × 3 mm × 1 mm glass sample containing 25 mol% Cs, the

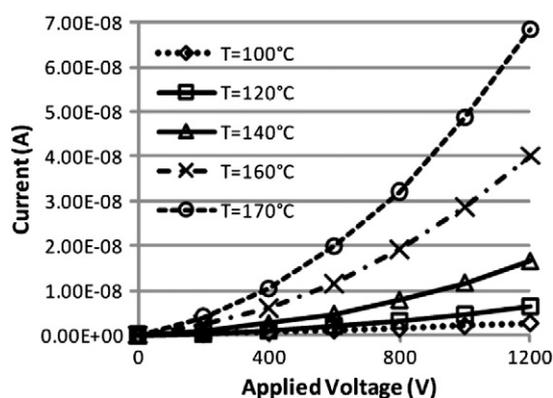


Fig. 4. Current–voltage data at temperatures between 100 °C and 170 °C heater setpoint.

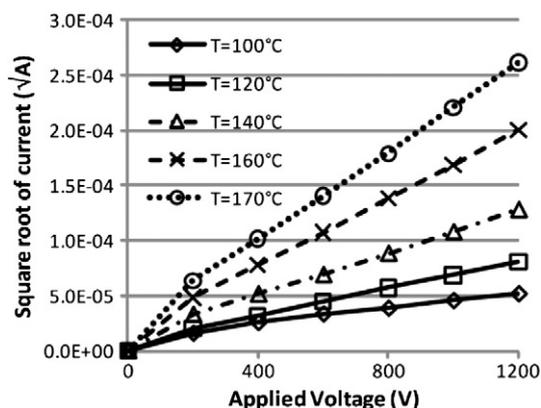


Fig. 5. Square root of current vs. voltage. Current proportional to  $V^2$  may indicate space charge limited current.

maximum capacity is 16 mg of Cs. This maximum capacity calculation assumes that neither the porous cathode nor the silver anode fails (e.g. by loss of adhesion) during the life of the source, and that the Ag ions sweep all the Cs from the glass. Extended life testing of these sources has not yet been conducted.

The non-linear dependence of current on voltage indicates that current is not limited by bulk resistivity. Plots of  $\sqrt{I}$  vs.  $V$  give straight lines (Fig. 5), indicating space charge limited conductance. However when glass samples were thinned from 0.95 mm to 0.2 mm, no corresponding increase in current was observed. Because of the digitated cathode metal, current crowding and space charge buildup may be occurring under the thin metal electrodes. Partially blocking cathodes can cause a pile-up of Cs ions beneath the cathode surface, causing an additional voltage drop [9]. We assume that the surface conduction of electrons from the cathode metal to the bare glass surface limits Cs generation, however Ag ion injection may also limit current.

Other glass systems, such as  $\text{Cs}_2\text{O}-\text{GeO}_2$  [10,11] and  $\text{Cs}_2\text{O}-\text{SiO}_2$  [12,13] have very high ionic mobility at  $\text{Cs}_2\text{O}$  mole concentrations higher than 25% and should be investigated. The primary disadvantage of these materials is that they are hygroscopic, which complicates handling and storage.

In summary, we have demonstrated a solid state alkali source which could be useful for compact vapor cells used in atomic clocks, magnetometers, MOTs, etc. Unlike previous work, no molten salt electrode is required, and the device does not need to be part of the

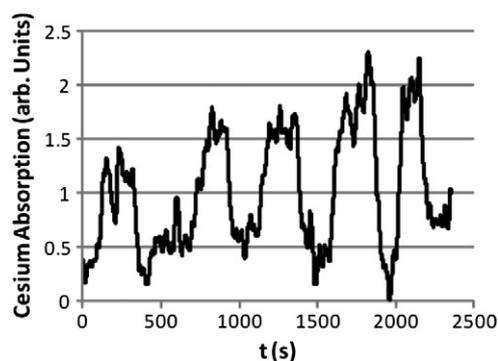


Fig. 6. Cs absorption signal immediately above a glass sample with star pattern cathode and thin film Ti/Au between fingers. Cs vapor generation is synchronous with applied 1.2 kV voltage.

vacuum chamber wall, i.e. the source and its electrodes are in the vacuum system.

#### Acknowledgments

This work was conducted under funding from DARPA IMPACT Phase 1, Contract Number N66001-09-C-2057. NSF support under grant DMR-0904615 is also acknowledged. The views, opinions, and/or findings contained in this article/presentation are those of the author/presenter and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

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