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Development of a Renewable Atomic Oxygen Sensor for Low Earth Orbit

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Introduction

THIS Note describes the design, development, and preliminary testing of a reusable atomic oxygen (AO) sensor for use in low Earth orbit (LEO). The most prevalent species in the Earth's thermosphere between the altitudes of approximately 150–650 km is AO.[1] The high orbital velocity of satellites in this region results in large fluxes of high-energy (~5-eV) atoms impinging on ram surfaces. The colliding oxygen atoms may simply scatter off, or they may form excited species that produce a glow that can interfere with the operation of optical systems.[2] Last, AO may erode exposed surface materials.[3] AO erosion results in mass changes; frequently other characteristics, such as the thermal radiative properties of materials, may also be changed.[4] Thus, changes of satellite temperature, contamination due to polymer chain fragmentation, and loss of power-generating capability may occur as a consequence of AO erosion.[3] Clearly, there is a requirement to develop sensors that can be used to characterize the AO environment that satellites experience.

Atomic Oxygen Measurement

Several techniques for measuring the AO environment have been developed. In general, an ideal sensor would be lightweight, small, accurate, and stable; would require low power; and would give time-resolved measurements of the AO flux. The simplest way of measuring AO exposure is to use a witness sample of a material whose erosion yield is well known. Although this method is lightweight, it suffers from many disadvantages; it can only give an indication of the total AO fluence and requires retrieval. Quartz crystal microbalances (QCMs) can provide a remote measurement of AO flux,[5] but their mass and power often make them unsuitable for small satellites, especially for multiple sensor operations.[6] Both witness samples and QCMs suffer from inaccuracies in material erosion yield values and from the fact that they can only be used for one set of measurements. Mass spectrometers have been used to characterize the ambient atmosphere and also AO/material reaction products.[7,8] Although they can give time-resolved readings of many species, they tend to be heavy and bulky and require considerable power, which often makes them unfeasible for microsatellite missions.

Thin film resistance sensors (actinometers) can be used to detect AO.[9] The resistance of a thin conducting film depends on its thickness and other dimensions. If such a film is reactive with AO, surface erosion reduces the conductor thickness, thereby causing a resistance increase. Films of silver have been used in this way; however, the AO fluence that can be measured by such films is restricted by a diffusion-limited regime due to the presence of an insulating oxide layer that forms on the conductor surface.[10] Carbon, which has volatile oxides (and thus does not suffer from the same problem as silver), has also been used.[11] Actinometers offer a simple, low-power, lightweight method and have been adapted for microsatellite use.[6,12] However, these sensors can only be used once and as a result of their low sensitivity can only record the AO fluence. Thus it seems that none of the sensors used to date satisfies the requirements of an ideal sensor.

Semiconducting Sensors

Semiconducting detectors (SCDs) have been used for gas detection since the discovery that the chemisorption of species onto the surface of a semiconductor changes the electrical characteristics of that sample, particularly the conductivity.[13] If thin films of the semiconductor are used, the induced surface changes dominate the bulk effects, and the detection of the surface conductivity is made easier. Commonly, metal oxide semiconductors have been used because the ionic structure of these materials means they have large band gaps and therefore a low number of intrinsic charge carriers. The majority of charge carriers are therefore extrinsic, and so the conductivity of the semiconductor sample is highly sensitive to any form of doping.

One of the main benefits of semiconductor sensors (apart from their light weight and small size) is the ability to regenerate their pre-exposure properties by heating, allowing the sensors to be reused many times.[14] Because resistance measurements are used as the gauge of chemisorption and hence AO exposure, they, like actinometers, require low power. However, unlike actinometers, SCDs can have high sensitivities; for example, the sensitivity of zinc oxide to AO has been found to be 10^9–10^{10} atoms cm^{-2} s^{-1} compared with ~10^{15} atoms cm^{-2} s^{-1} for silver films[15,16] (based on the data in Ref. 16 and the assumption that the pulsed AO source was run at ~3 Hz). Thus it would seem that a sensor based on semiconducting metal oxides may satisfy most of the criteria of an ideal sensor.

Such sensors have been adapted for pulsed-mode AO sensing in the lower thermosphere on board a sounding rocket[15] but, so far, have not been used continuously in space. The remainder of this Note will describe the development of a microsatellite experiment based on SCDs.

Experimental Development

Laboratory testing in the pulsed laser AO facility at the European Space and Technology Centre shows that the resistances of zinc oxide single crystals increase under the action of AO flux. The increase in resistance is brought about by the localization of electrons from the conduction band by the adsorbed AO. The resistance increase is also shown to be reversible. Figure 1 is a graph of an exposure/regeneration cycle for a single crystal. It can be seen that the rate of resistance change increases when the AO flux was switched on and stops increasing when the AO was switched off and the regeneration commenced. The same figure shows the temperature of the crystal during exposure and the effect of heating the crystal to ~350 K: it is evident that, when the sensor reaches the temperature recorded before AO exposure, the resistance of the

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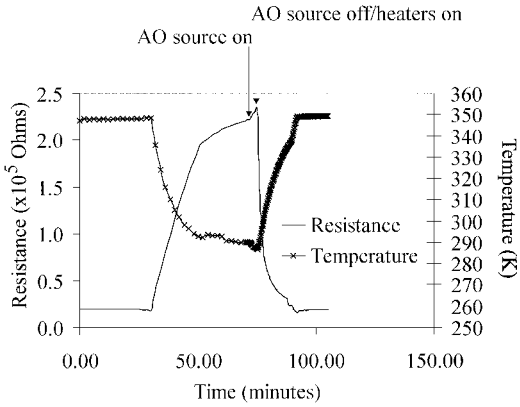

Fig. 1 Example of the response of zinc oxide to AO exposure.

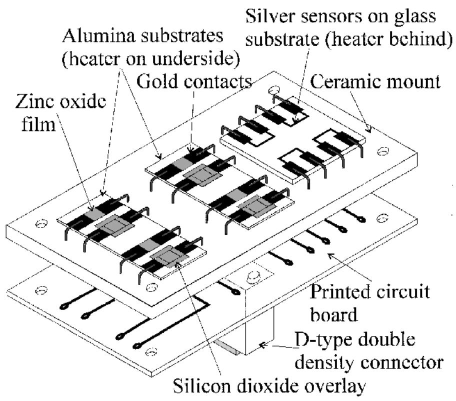

Fig. 2 Schematic of the sensor unit of AOE-2.

semiconductor has recovered to nearly the pre-AO exposure resistance value. Thus this cycle can be used repeatedly to measure AO fluxes. It has been found that both the rate of increase of the resistance and the saturation resistance are functions of the flux of AO and, as such, can be used as the measured in a detector circuit.

Currently an experiment (AOE-2) for flight on the United Kingdom's Defence Evaluation and Research Agency microsatellite STRV1-c, scheduled for launch in 1999, is being developed to demonstrate the use of these sensors in space. The satellite will be placed into a geostationary transfer orbit (by an Ariane 5 launch vehicle) and will be periodically exposed to high-energy AO during the perigee pass.

The semiconducting material will be zinc oxide in thin-film form because it has been found that thin films are easier to package into a space-rated unit than the single crystals used in the preliminary laboratory studies reported here. The thin films of metal oxide are sputter deposited onto thin, high-purity (99.6%) alumina substrates with evaporated gold tabs to provide contacts for resistance measurement. Each sensor consists of four films, two exposed to the AO environment and two covered with a layer of silicon dioxide. The silicon dioxide overlay (Fig. 2) has been incorporated so that the photoconductive effect due to solar uv can be deconvoluted from the bare sensor readings (which record the resistance change due to both AO and uv). The semiconducting films require regeneration after, and temperature control during, AO exposure at perigee. For this purpose each substrate has a thick film resistance heater (made from ruthenium oxide in a glass frit) deposited and fired on the opposite side of the alumina substrate to the thin films. Each heater has a temperature sensor for temperature control.

The experiment has been divided into two units, a sensor unit and an electronics unit, for ease of mounting and placement on the satellite. The sensor unit carries eight zinc oxide films (four bare and four covered with quartz) of two thicknesses and four silver thin films. The electronics unit contains the circuitry for two-point film resistance measurement, power conditioning, and heater control. The maximum power consumption of the experiment is 3 W, and the total mass is 0.35 kg. To reduce the possibility of AO-induced contamination of the films, a ceramic sheet, which is resistant to AO attack and is low outgassing, is used to support the sensors instead of a polymer. The sensor patch is designed to bolt onto an exterior face of the satellite that receives periodic AO exposure (the satellite will be spin stabilized), whereas the electronics unit resides in the satellite interior; a harness connects the two.

The operation of the experiment will be in two modes; the first is the measurement mode and will occur near perigee, i.e., when the AO acts on the semiconductor and alters its resistance. The second is the regeneration mode and will be activated well outside of the atmosphere, at around 10,000-km altitude. At this altitude there will be no AO, and so, by the use of the heater, the SCD films can be renewed for the next perigee pass.

Conclusions

There is a need to characterize the LEO AO environment; none of the methods used to date conforms to the ideal characteristics of low power, light weight, reusability, and high sensitivity. However, semiconducting metal oxide sensors may provide such a technique. Preliminary laboratory results have demonstrated that zinc oxide single crystals can be used to measure AO fluxes. It has also been demonstrated that such sensors can be regenerated so that the sensor can be reused many times. The design of a low-power and lightweight spacecraft experiment using sensor elements fabricated from zinc oxide thin films for launch on board a microsatellite has been described.

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