MICRO/NANOFABRICATED SOLID-STATE THERMOELECTRIC GENERATOR DEVICES FOR INTEGRATED HIGH VOLTAGE POWER SOURCES

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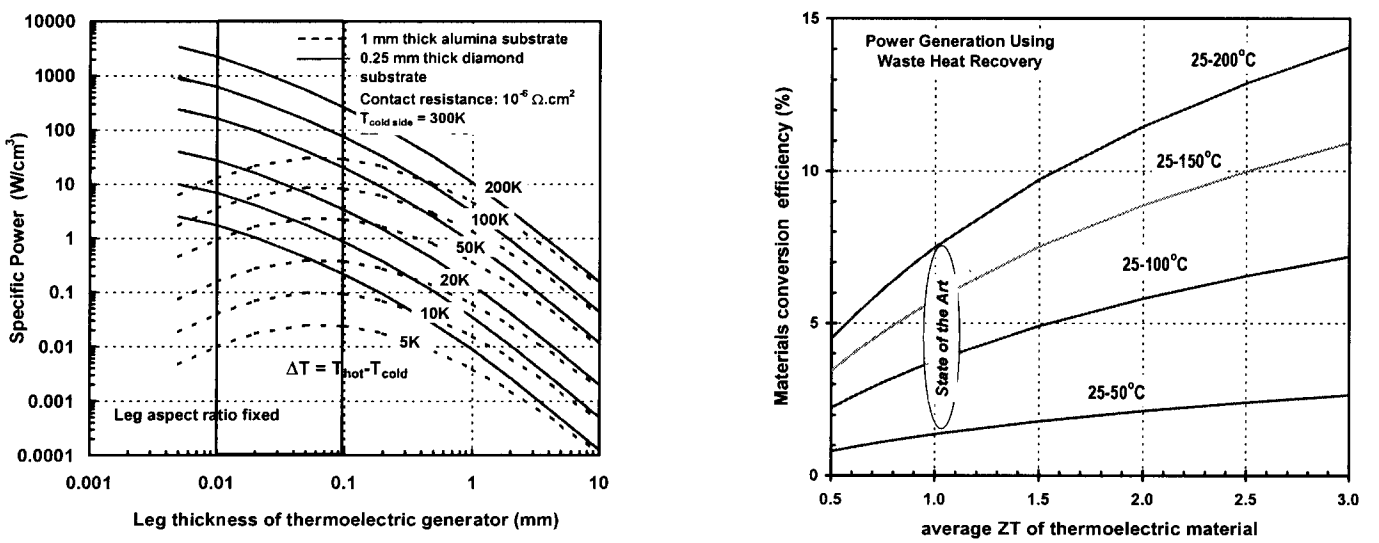
Introduction

Deep space missions have a strong need for compact, high power density, reliable and long life electrical power generation and storage under extreme temperature conditions. Except for electrochemical batteries and solar cells, there are currently no available miniaturized power sources. Conventional power generators devices become inefficient in extreme environments (such as encountered in Mars, Venus or outer planet missions) and rechargeable energy storage devices can only be operated in a narrow temperature range thereby limiting mission duration. The planned development of much smaller spacecrafts incorporating a variety of micro/nanodevices and miniature vehicles will require novel, reliable power technologies. It is also expected that such micro power sources could have a wide range of terrestrial applications, in particular when the limited lifetime and environmental limitations of batteries are key factors. Advanced solid-state thermoelectric combined with radioisotope or waste heat sources and low profile energy storage devices are ideally suited for these applications. Direct energy conversion solid-state alpha-voltaic devices are also of interest due to their potential for high conversion efficiency without the need for elevated temperatures. The Jet Propulsion Laboratory (JPL) has been actively pursuing the development of thermoelectric micro/nanodevices that can be fabricated using a combination of electrochemical deposition and integrated circuit processing techniques. Some of the technical challenges associated with these micro/nanodevice concepts, their expected level of performance and experimental fabrication and testing results to date are presented and discussed.

Thermoelectrics

Solid-state thermoelectric devices have demonstrated attractive characteristics such as long life, the absence of moving parts or emissions, low maintenance and high reliability [1]. In spite of a large number of potential civilian and military applications, their use has been severely limited due to their relatively low energy conversion efficiency and high development costs. To broaden the field of thermoelectrics, higher performance devices and systems need to be developed. Higher performance can consist of increased device energy conversion efficiency, or improved device design to meet challenging applications, or both efficiency and design.



(a) (b)

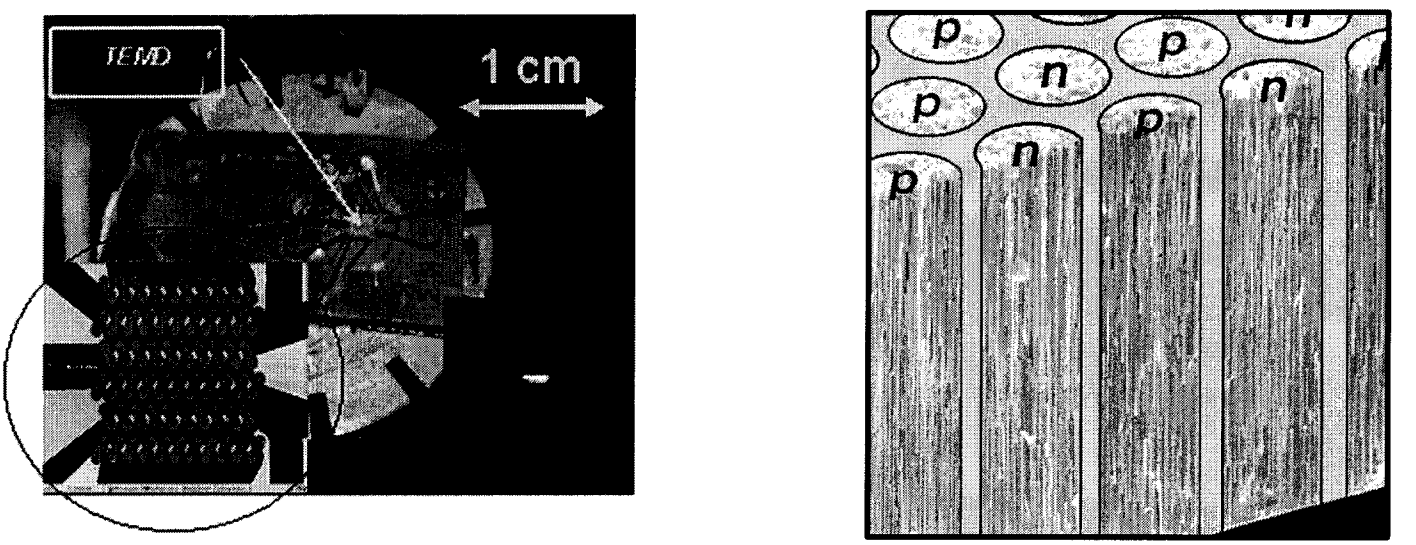
Figure 1 (a). Calculated increase in power density with increasing device miniaturization and increasing temperature differential of operation. Data are shown for both low (alumina, dotted lines) and high (diamond, plain lines) thermal conductivity substrates. The calculation for increasingly miniaturized devices implies a corresponding increase in heat flux density. (b). Calculated improvement in thermoelectric generator performance when using more efficient materials. The temperature differences reported here are relevant to state-of-the-art Bi_2Te_3 alloys and miniaturized devices.

Thick Film-Based Microdevices

A key feature of thermoelectric devices are their geometrical scalability, as illustrated in Figure 1a. Note that the maximum electrical power output, is directly proportional to the *A/l* leg geometric aspect ratio, so that power densities are inversely proportional to the leg length. Also, the electrical output voltage of a thermoelectric generator is directly proportional to both the number of elements connected in series and the temperature differential between the hot and cold junctions. Consequently, orders of magnitude increases in the specific power (watts per unit area or volume) of power generation devices can be achieve even when using state-of-the-art thermoelectric materials if the thickness of such devices can be scaled down to tens of microns instead of several millimeters in conventional bulk devices. In addition, developing the ability to fabricate devices with tens of thousands of microelements instead of a couple of hundreds millimeter sized legs would enable voltage output of tens of volts at temperature differentials of only a few degrees. Current thermoelectric module technology is ill suited to the development of miniaturized devices due to mechanical and manufacturing constraints for thermoelements in both dimensions and number. In addition to the widespread use of semi-manual assembly techniques that results in high costs for more compact configurations, these devices have typically undesirable high current and low voltage characteristics. To circumvent key shortcomings of the current bulk and thin film technologies, JPL is pursuing the development of thermoelectric microdevices that can be fabricated using a combination of electrochemical and integrated circuit processing techniques [2]. Building on the availability of thick photoresist commercial products and using conventional UV-photolithography, templates suitable to the electrochemical deposition of legs as thick as 80μm and as small as 6μm in diameter have been developed. The thick photoresist template is patterned with deep square or round shaped holes that must be pre-aligned on top of metallic interconnects.

More processing steps are required to successively deposit n-type and p-type legs on top of the bottom substrate interconnects, and then ensure proper joining to a top substrate with similarly patterned electrical interconnects. . The result of these processing steps is illustrated in Figure 4 and 5. The combination of ECD and IC-type techniques offers a degree of flexibility in designing and fabricating thermoelectric microdevices. A single photolithography mask can usually combine all of the necessary patterns to completely fabricate one microdevice configuration.

Many microdevice structures with various configurations have been fabricated to date. Based on the known properties of the Bi_2Te_3 alloy legs, resistance measurements of individual strings and complete devices indicated that electrical contact resistivity values as low as 10^{-8} $\Omega.cm^2$ can be achieved by optimizing the fabrication process. Both electronic cooling and power generation microdevice operation have been demonstrated very recently, as well as the ability of such devices to remain mechanically and electrically stable after exposures to elevated temperatures (as high as 300°C). There is still more work left though, to optimize and characterize fully the performance of such devices [3].



(a) (b)

Figure 2.(a) Electrical and thermal characterization of thermoelectric microdevices fabricated using electrodeposited Bi_2Te_3 legs on top of Au interconnect metallizations and using a Si/SiO_2 substrate. This device has 122 legs interconnected in series (b) : Illustration of the quantum nanowire based micro power generator configuration

Nanowire-Based Microdevices

By manipulating electrical and thermal transport on the nanoscale, it appears more and more convincingly possible to increase significantly the dimensionless figure of merit ZT [4] and as a result improve the thermoelectric conversion efficiency, as calculated in Figure 1b. This can be achieved in various ways, such in having a very large density of states

just above the Fermi level (large Seebeck), separating doping impurities from charge carriers (high mobility) or efficiently scattering heat carrying phonons (low lattice thermal conductivity). Such effects have been predicted in low dimensional semiconductor structures such as superlattices (2D), nanowires (1D) and quantum dots (0D). Recently several experimental results have shown that dramatic increase in electrical power factor (S^2/ρ) and decrease in lattice thermal conductivity was possible in superlattice structures [5-6]. However, the use of superlattices in thermoelectric microdevices still constitutes a daunting challenge because of fabrications and operation issues. Interestingly, using nanowires to fabricate microdevices may be an easier problem, since the nanowires are typically grown inside of a template that can be used for structural support. Several research groups are now working on the synthesis and characterization of nanowires from Bi, Bi_2Te_3 and other thermoelectric materials. The JPL group is concentrating its efforts on n-type and p-type $Bi_{2-x}Sb_xTe_3$ nanowires as long as 60μm grown in 10 to 200nm size anodized alumina templates, (Figure 2b), and work on prototype devices based on such nanowires is underway.

Alpha-VoltaicMicrogenerators

Another attractive solid state power generator device investigated at JPL for enabling "system on a chip" architectures is based on the direct conversion of the kinetic energy of alpha particles into electricity [7] as described in Figure 3. This device is expected to exhibit a high conversion efficiency (over 10%) and to function continuously over a long period of time in the temperature range of 20 to 800K without any recharging needs or the presence of any sunlight thanks to a unique long life design.

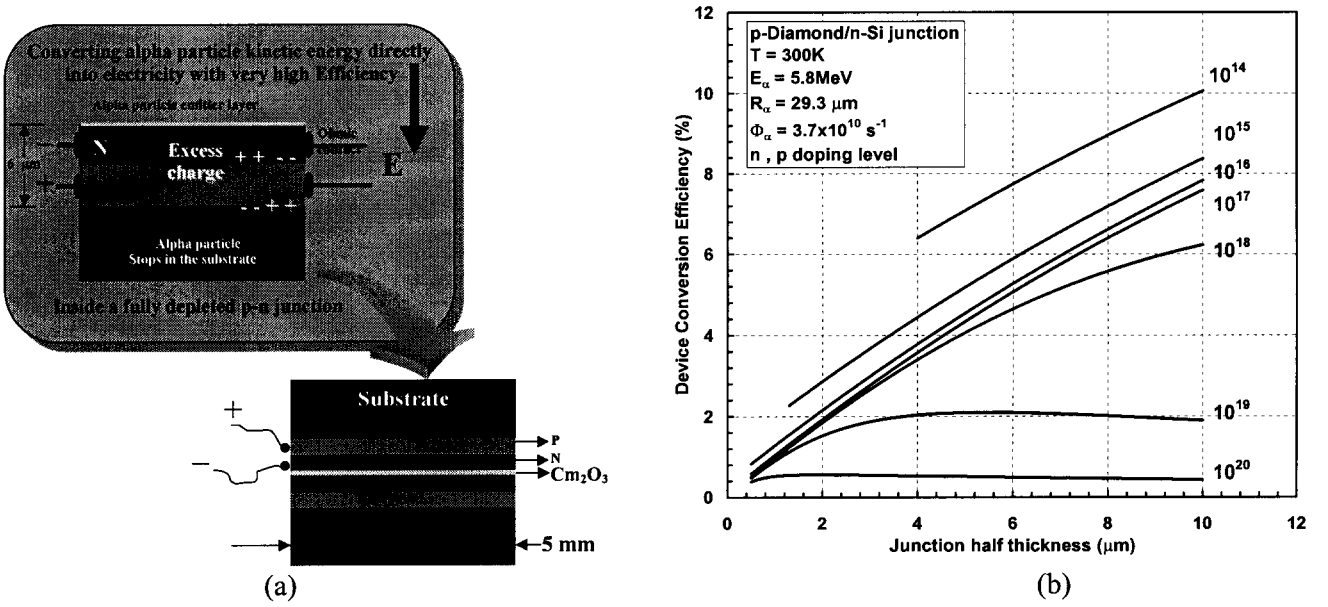
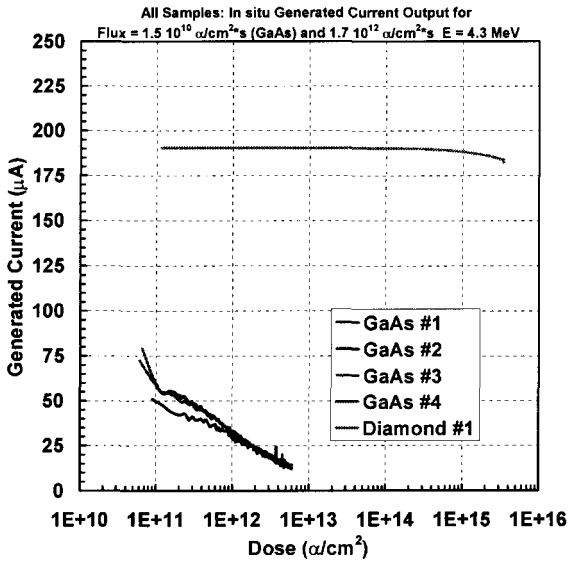


Figure 3. (a) Schematic representation of an alpha-voltaic power generator device. The emitted high-energy alpha particles cross the thin depleted semiconductor p-n junction, creating electron-hole pairs that are collected at the metallic contacts. Most of the lattice damage from the alpha particle kinetic energy occurs in the inactive substrate layers. (b) Predicted conversion efficiency for alpha-voltaic device based on Si and diamond films as a function of doping level.

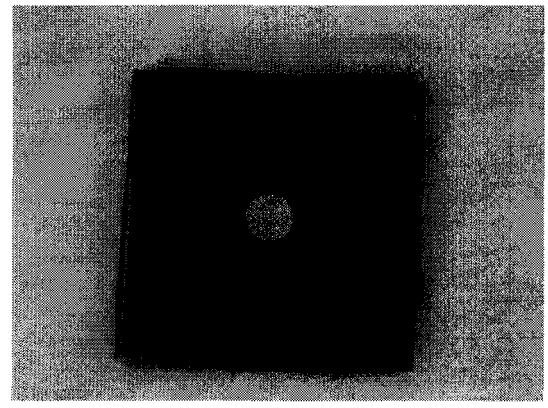
The use of alpha particle kinetic energy for conversion into electricity using an existing SiC photodiode was reported earlier [8]. This particular device was found to have degraded in a rapid manner because it was not specifically designed to avoid the crystal damage from implanted alpha particles. Results on similar devices using beta and gamma rays were also published [9], but these power sources exhibited extremely low conversion efficiency (0.1 to 4%) and required substantial shielding to reduce the dose from its radiation to adjacent electronics. Such devices also had a relatively short lifetime (2-6 years) and delivered very low power levels (a few milliwatts).

The alpha-voltaic microgenerator device design pursued by JPL is aiming at minimizing lattice damage from alpha particles in the active semiconductor p-n junction, as illustrated in Figure 3. The key design feature of the technology lies in the determination of the diode dimensions so that alpha particles with energy ~6 MeV do not stop in the active device volume but in the inactive substrate layers. Alpha particles cause severe lattice damage when they stop since they lose a large fraction of their kinetic energy just before stopping in materials. Nevertheless, some lattice damage is expected in the active p-n junction, but it has been observed that such damage is continuously annealed during the ionization process in semiconductors. Semiconductors such as GaAs that are stable at high temperatures have been used in the fabrication of the alpha particle-based power source. Curium-244, a nearly pure alpha particle source with negligible soft gamma emission and an 18-year half-life has been initially selected as the radioisotope material. Initial studies indicate that

optimally configured miniaturized alpha voltaic power sources could offer high specific power values close to a milliwatt per cubic millimeter (mW/mm^3). Several batches of p+/p/n/n+ GaAs alpha-voltaic devices with doped contacts have been processed and fabricated. But performance characterization during in-situ characterization has shown so far, that in spite of thicker doped regions and thin 2 μm p/n active layers, rapid degradation of the generation current occurs (Figure 4.a). Simulations using exact interatomic potential that describes bonding and chemistry of GaAs have indicated that antistructure defects generated by irradiation damage could be a major factor in GaAs-based alpha-voltaics. Other semiconductors more resistant to radiation damage are currently being considered. Much more encouraging results have been recently obtained with diamond on Si device structures and this work is in progress (Figure 4.a, 4.b)



(a)



(b)

Figure 4: (a) Output current versus time for GaAs-based alpha-voltaic devices. Initial output power of 90μW rapidly decreases to about 10μW after only 10 minutes. Preliminary results for diamond/Si hetrostructure devices are much more promising, and demonstrated lower radiation damaged as well as ability to heal damage through short high temperature anneals. (b) Picture of actual diamond/Si device with metallization on diamond side.

Acknowledgments

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