Sensors and Actuators A 103 (2003) 253–262

www.elsevier.com/locate/sna

Igniters and temperature sensors for a micro-scale combustion system☆

Xin Zhang[a,*], Amit Mehra[b], Arturo A. Ayón[c], Ian A. Waitz[b]

[a]Department of Manufacturing Engineering and Fraunhofer USA Center for Manufacturing Innovation, Boston University, Boston, MA 02215, USA
[b]Gas Turbine Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[c]Sony Semiconductor, 1 Sony Place, San Antonio, TX 78245, USA

Abstract

This paper presents the development of micro-fabricated "on-chip" polysilicon igniters and temperature sensors for the combustion system of a micro-gas turbine engine. We have reported the design and fabrication results of a novel through-wafer interconnect scheme that could greatly facilitate electrical contacts in multi-level MEMS devices by allowing direct electrical access to the backside of a wafer. This paper presents the results of a further effort that uses these interconnects to make electrical contacts to a thin-film polysilicon resistor so as to evaluate its ignition capability and its use as a wall temperature sensor for the micro-gas turbine engine. An application of the through-wafer interconnects to a concept demonstration of thin-film polysilicon resistive igniters for the micro-engine showed that it was possible to initiate combustion and locally raise the temperature of the igniter to 900 °C so long as the chip is thermally isolated. The results were found to be in good agreement with the predictions of an FEM thermal model. The possibility of using the resistors as temperature sensors is also examined. The non-linear variation of polysilicon resistivity with annealing temperatures due to complex effects resulting from dopant atom segregation, secondary grain growth and crystallographic relaxation reduced the operating range of the sensors to 450 °C.

Keywords: Igniters; Temperature sensors; Electrical interconnect; Power MEMS

1. Introduction

As part of an initiative to develop a new generation of silicon power MEMS, an effort is currently underway to produce 10–50 W of electrical power in a package that is less than 1 cm^3 in volume. The baseline design, applications and operation of such a device is presented by Epstein et al. [1]; the various turbomachinery, rotor-dynamic, electrical and combustion components are described in Refs. [2–5].

Since such an engine will require electrical connections to the diagnostic elements and electrical components, it is necessary to develop a reliable electrical interconnect scheme. We have reported the design, fabrication, and experimental demonstration of through-wafer interconnects capable of allowing direct electrical access to the interior of a multilevel micro-electromechanical system device [6]. The interconnects exploit the ability to conformally coat a high aspect ratio trench with a thick layer of tetraethylorthosilicate (TEOS) to isolate a through-wafer silicon plug that can provide electrical contact across two sides of a low resistivity wafer.

The difficulty in instrumenting micro-scale devices with conventional diagnostics also motivates the need for in situ sensors that are routinely micro-fabricated onto the chip as part of the fabrication process. In addition, since the final packaged device is intended to be a self-contained unit that is capable of independent operation, it will also require on-chip igniters to initiate combustion and start the heat engine.

This paper presents a concept demonstration of through-wafer interconnect application to thin-film polysilicon igniters and temperature sensors, and examines their behavior under high temperature operating conditions.

2. Design concept

The concept of an on-chip igniter is a simple one—a thin-film of a conductive material is laid down along the inner wall of the combustor and patterned in the shape of a resistor. Upon passage of current, this resistive element heats up and initiates combustion. There are four requirements for such an element. First, it should be able to heat the mixture up to its point of ignition while consuming no more than a few Watts of power (~600 °C for a hydrogen–air mixture and

☆This paper was presented at the 15th IEEE MEMS conference, held in Las Vegas, USA, January 20–24, 2002, and is an expansion of the abstract as printed in the Technical Digest of this meeting.

* Corresponding author. Tel.: +1-617-358-2702; fax: +1-617-353-5548.
E-mail address: xinz@bu.edu (X. Zhang).

0924-4247/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0924-4247(02)00344-8

~200 °C for a hydrocarbon–air mixture). Second, it must be placed within the combustor recirculation zone to facilitate ignition. Third, it must survive exposure to wall temperatures up to ~1000 °C. Finally, it must be compatible with electrical leads that connect to the outside of the device, and with the overall fabrication sequence of the engine.

The concept of using the same igniter as a wall temperature sensor is based on an in situ resistance measurement to back-out its operating temperature from the temperature coefficient of resistance (TCR) of the material. There are also four requirements for such a wall temperature sensor. First, it must be in good thermal contact with the wall. Second, the resistivity change with temperature should be measurable in the room temperature–1000 °C range. Third, it must not degrade in the high temperature environment of the engine. Finally, it must be compatible with electrical leads and with the overall fabrication sequence of the engine.

Although thin-film resistors are routinely used in the integrated circuit industry, the primary challenge herein lies in operating them at combustion temperatures in the 1300–2000 °C range, and being able to make electrical contacts to them inside a multi-level MEMS device.

Igniters and temperature sensors for the micro-engine combustor are comprised of a thin layer of conductive material that is patterned in the shape of a resistor and isolated from the underlying substrate via an oxide layer. While typical applications for resistors in the integrated circuit industry have utilized metals such as aluminum, gold and platinum, the high temperature environment of the combustion chamber precludes their use for igniters and temperature sensors in the micro-engine combustor. Gold and aluminum will melt at the operating temperatures of the combustor; platinum is known to agglomerate at temperatures above 700 °C [7]. Other high temperature metals such as nickel and molybdenum were also considered, however, they are also known to degrade due to the formation of silicides at temperatures around 800 °C [8].

Similar to previously reported high temperature applications [9,10], polysilicon was therefore selected as a suitable material for the thin-film igniters because (i) it is integrable with the fabrication sequence for a silicon engine, (ii) CVD polysilicon has the desirable temperature and structural capabilities for the application, (iii) its resistivity can be tailored by controlling the dopant concentration, and (iv) thin film polysilicon resistors have previously been demonstrated to produce Joule heating up to 1200 °C without exhibiting severe electromigration effects [9].

Following the selection of a suitable material, a test device comprising eight different geometrical designs was fabricated. These were based on devices reported by Cole et al. [9], and were only intended for use in a short-loop experiment to identify suitable resistor geometries. The resistors on this chip were designed to operate at a current density of 2×10^5 A/cm^2 based on previously reported observations of incandescence in doped polysilicon resistors at this current density level [9]. The resulting designs had linewidths between 10 and 25 μm, lengths of approximately 1 mm, and overall resistances between 1 and 14 kΩ. The polysilicon thickness was 0.25 μm, its sheet-resistivity was approximately 10 Ω/sq, and the insulating oxide thickness was 0.5 μm.

Preliminary testing of the resistors showed that it was possible to raise the temperature of the chip to approximately 700 °C by passing current through the 12 kΩ resistor. Prior to further integration with the rest of the device, however, two additional issues needed to be resolved. First, infra-red (IR) camera images showed that the heating was not localized around the igniter. Instead, the resistor dissipated a significant amount of heat into the supporting substrate, raising the temperature of the entire chip to 700 °C. While this was acceptable from a combustion ignition perspective, it utilized more power than was necessary to locally heat and ignite the mixture. Consequently, future designs were intended to incorporate 2 μm thick oxide layers to improve the thermal insulation between the heating element and 2 μm oxide was found to be the thickest layer that could be deposited and densified without introducing excess wafer bow or stress-induced cracking. Second, the igniters required sealed wafer-level leads along bondlines to make electrical contacts to an external power supply. While this scheme was acceptable for the three-stack micro-engine combustor, it would sacrifice the insulating properties of the recirculation jacket in the final engine configuration. Consequently, a new electrical interconnect scheme that obviated the need for taking lateral electrical leads through the recirculation jacket was developed.

As described earlier, the difficulty in taking out sealed wafer-level leads through bondlines motivated the development of a through-wafer interconnect scheme to allow direct electrical contact to the backside of the wafer. Conceived by Schmidt and coworkers [6] and illustrated in Fig. 1, the use of this novel technique can be expected to facilitate electrical connections in other micro-fabricated devices as well. The concept of this through-wafer interconnect exploits the ability to conformally coat a high-aspect ratio trench with a thick insulating layer so as to isolate a through-wafer via that can be used to provide electrical contact across two sides of a low-resistivity wafer. A fabrication demonstration and application of these interconnects to make electrical contacts to a second build of igniters and temperature sensors for the micro-engine has been reported elsewhere [6].

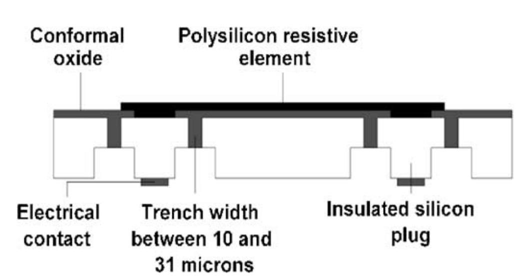


Fig. 1. A schematic representation of a polysilicon resistive element connected by two through-wafer interconnects.

Using deep reactive ion etching (DRIE), 100 μm deep circular trenches were etched into the top surface of 300 mm n-type ⟨1 0 0⟩ silicon wafers that had a resistivity of 0.01–0.02 Ω cm. A 10 μm coating of TEOS was then deposited at 350 °C in order to isolate the silicon plug from the rest of the substrate. Following the TEOS deposition, the oxide was chemically mechanically polished down to the silicon surface to allow subsequent photolithography steps. The 2 μm of TEOS was then additionally re-deposited and patterned to provide electrical access for the polysilicon. 0.5 μm thick polysilicon was then deposited at 625 °C, $POCl_3$ phosphorus-doped at 925 °C, and patterned to define the resistors. The resistor linewidth was 20 μm; the length was 2 mm. The design sheet resistivity was 10 Ω/sq; the overall design resistance was approximately 5 kΩ. Finally, 100 μm wide circular trenches were dry-etched from the backside to release the isolated silicon plugs and provide electrical contact across the two sides of the wafer.

3. Igniter development

Isolated igniter tests were conducted by using probe-tips to apply a voltage across the backside of the interconnect-pairs.

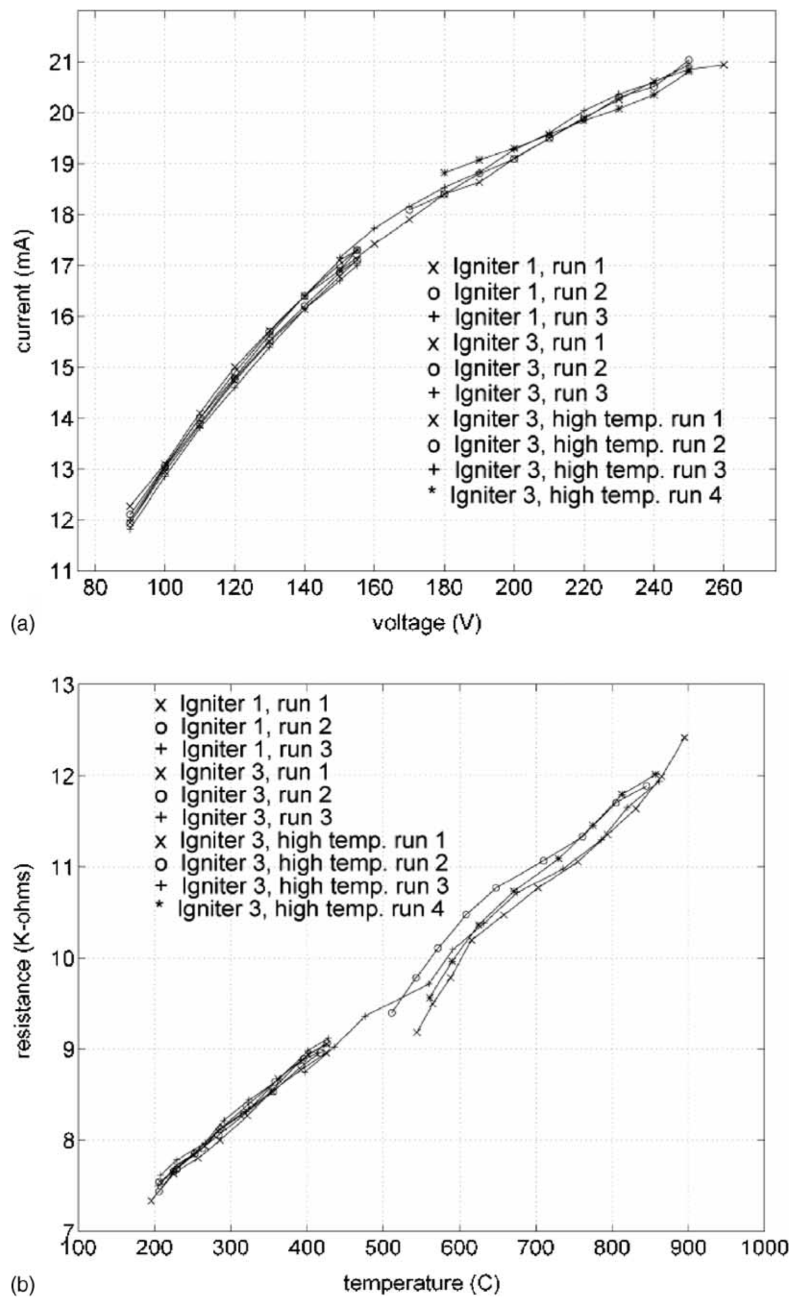


Fig. 2. *V–I* and *R* versus *T* curves for the igniter. (Note: the different curves represent multiple tests on two different samples for two different temperature ranges of the IR camera.)

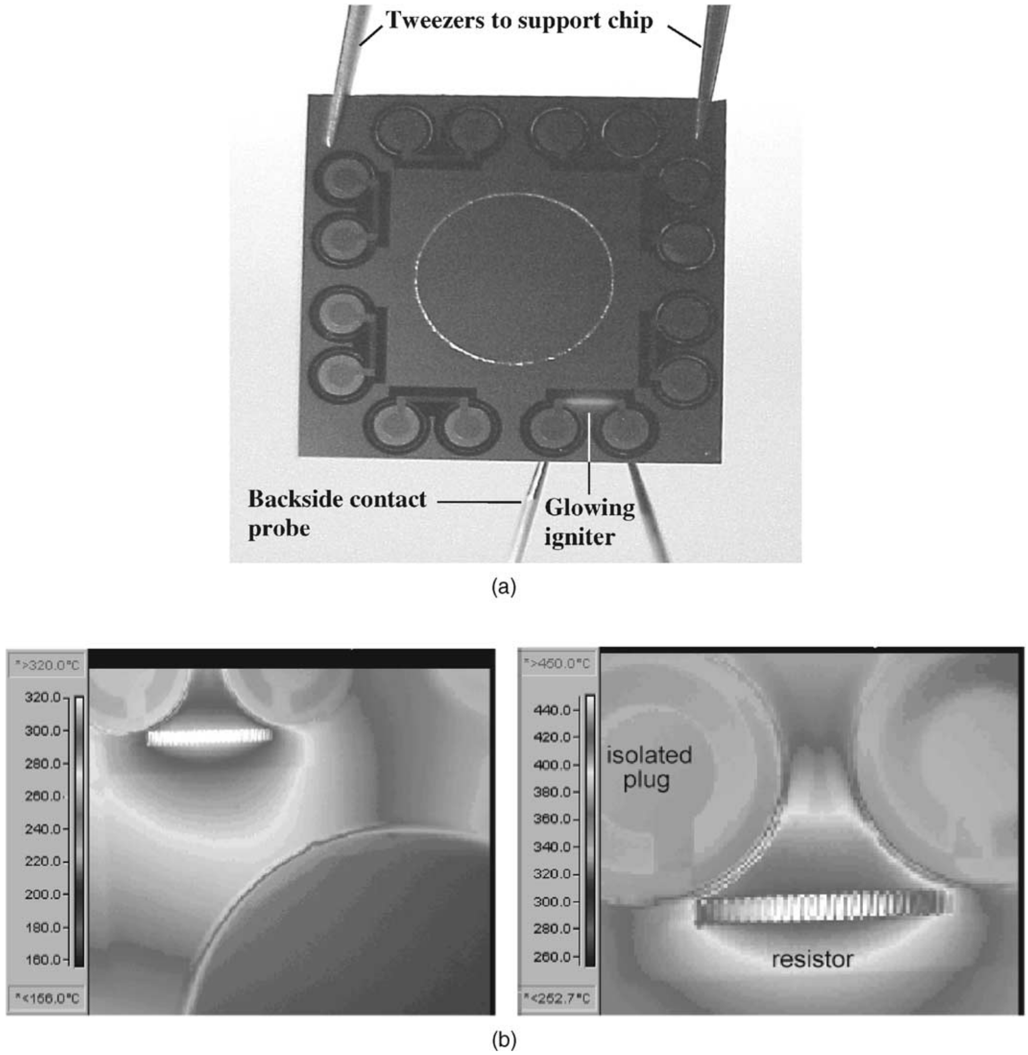


Fig. 3. Optical and IR images of an igniter showing localized heating.

Fig. 2 shows the resistance and applied power as a function of the igniter temperature. The igniter temperature was measured with an IR camera calibrated to a polysilicon emissivity of 0.5. The figure shows increasing resistance and temperature with input power. The igniter current is of the order of tens of milliamperes, and corresponds to the intended current density of 10^5 A/cm^2. Fig. 2 also shows that the power utilization of the igniters is between 3 and 6 W. In addition to depicting ohmic behavior over most of the operating range, the igniters were also observed to exhibit localized heating. Finally, Fig. 2 shows experimental results for multiple runs, and for multiple dies, and indicates good repeatability of the results.

The igniters exhibited localized heating upon passage of current; Fig. 3 shows two IR and one optical image showing the localized nature of this heating. The ignition capability of the igniters was also confirmed by passing a combustible hydrogen–air mixture over a single heater element (as shown in Fig. 3). The igniter was able to reach a temperature of

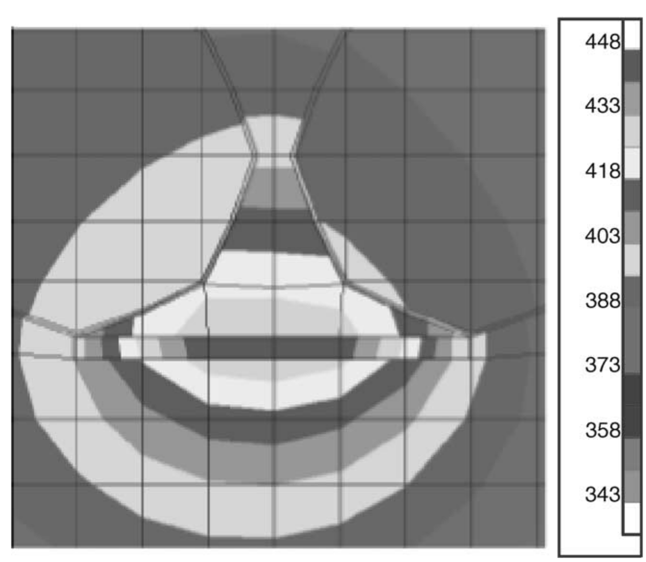


Fig. 4. Sample surface temperature distribution as obtained by the FEM thermal model, showing good qualitative agreement with the image in Fig. 3.

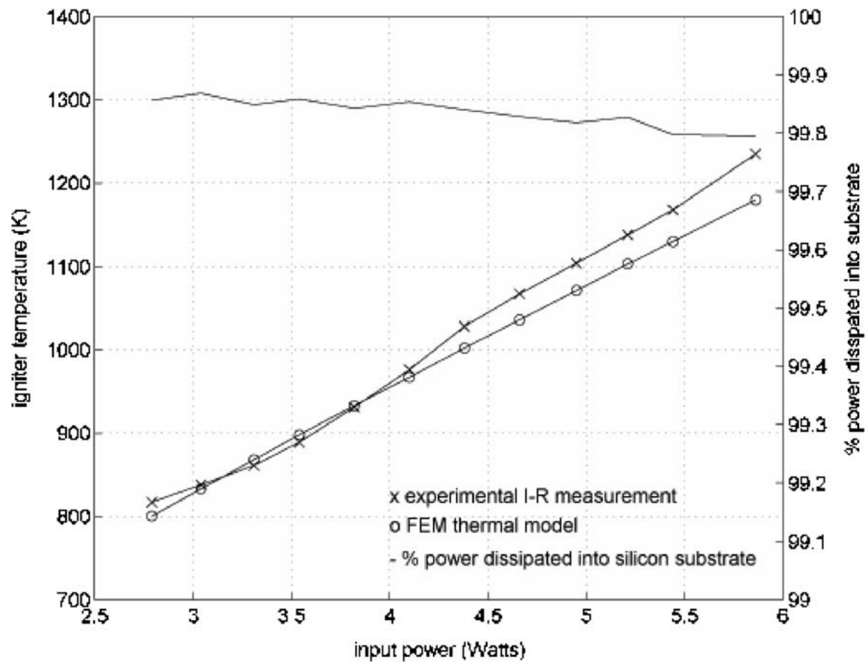


Fig. 5. Numerically predicted values of the igniter surface temperature, showing good comparison with the experimental data.

~900 °C and repeatedly ignite the mixture while consuming approximately 5 W of power.

However, upon integration with the rest of micro-engine combustor that comprised three silicon wafers fusion bonded together in a confined stack [4], the igniter was unable to initiate combustion. This behavior was attributed to the ‘‘heat-sinking’’ effect from the rest of the silicon structure which prevented the heater from reaching the 900 °C empirically observed to be necessary for ignition.

To confirm this hypothesis, a finite-element heat transfer model was subsequently developed. Fig. 4 shows a resulting sample surface temperature distribution as obtained from the model. This is similar to the IR temperature distribution shown in Fig. 3. Fig. 5 plots the igniter surface temperature

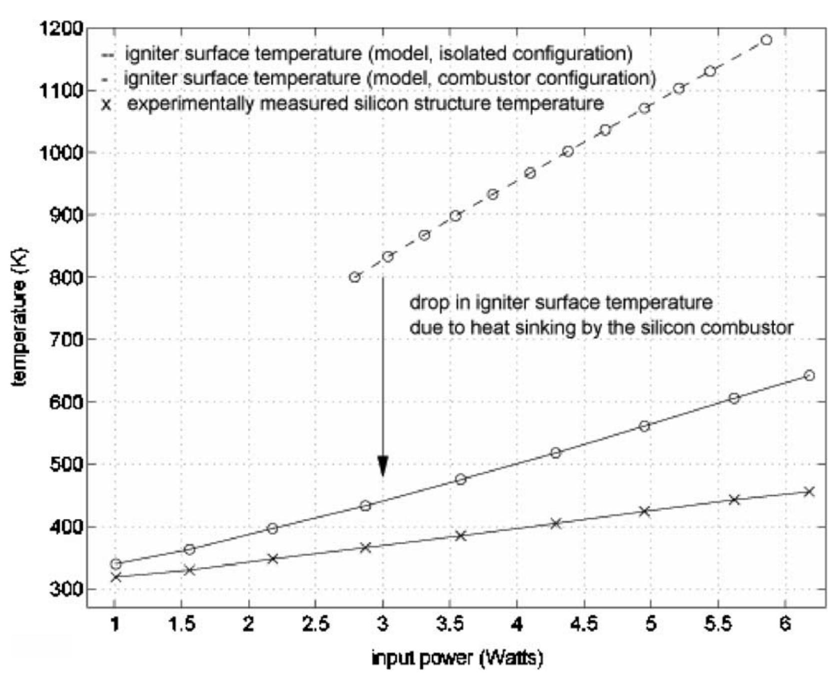


Fig. 6. Igniter surface temperature in the integrated combustor, showing a significant drop from the isolated configuration.

as a function of the input power and compares it with the experimental IR measurements. The numerical results agree with the experimental measurements to within 55 °C, and suggest that the simplified resistor and interconnect geometry is sufficient to capture the temperature behavior of the igniter. Fig. 6 plots the amount of heat being conducted into the substrate, and shows that most of the input power is being dissipated via the silicon.

Efforts are currently underway to improve the ignition capability of the igniters in a confined configuration by partially under-cutting the oxide below the resistor in order to reduce the heat loss to the silicon substrate. Results from the FEM model show that suspending the polysilicon above a 2 μm air gap can increase the igniter surface temperature by up to 1000 °C, however, isolation of the igniters in such a manner could increase their susceptibility to high temperature combustion gases. The functional design of the micro-engine igniter may therefore have to be traded-off against its durability, and is currently being re-evaluated for future builds.

4. Temperature sensor development

This section discusses the use of the polysilicon resistors as temperature sensors for the engine. Use of the resistor as a temperature sensor is based on the ability to calibrate its resistance as a function of temperature, and then use an in situ measurement of the resistance to determine its temperature during operation. Fig. 2(b) shows a calibration curve obtained from the resistance versus temperature data for various igniter runs. The temperature–resistance relationship for the sensor was obtained by linearly fitting the data in Fig. 2(b), and is given by: $R\,(\mathrm{k}\Omega) = 6.1389 - 0.0068T\,(^\circ\mathrm{C})$.

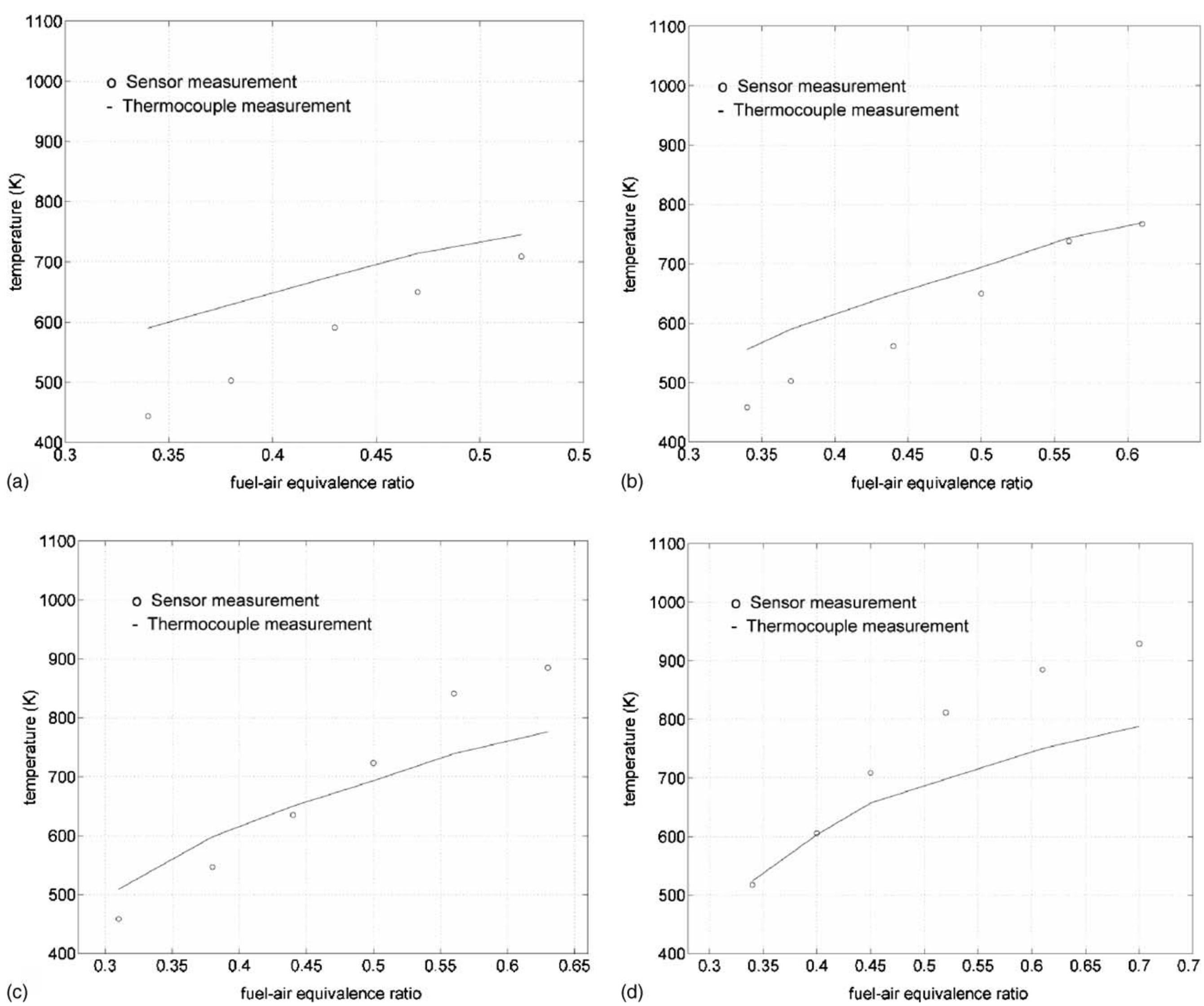


Fig. 7. Comparison of the sensor measurements with thermocouple data, showing a monotonic increase in the resistance-based measurements with progressive high temperature exposure: (a) Run 1; (b) Run 2, after 1 h of exposure; (c) Run 3, after 2 h of exposure; (d) Run 4, after 3 h of exposure.

To test this capability, the resistors were exposed to a combustion environment with equivalence ratios between 0.3 and 0.7. The resistance-based sensor measurements were then compared with independent measurements from an adjacent thermocouple, and are plotted in Fig. 7 for different exposure times. The results show that the resistance-based measurements from the sensor differ by as much as 150 °C from the thermocouple results. The difference in the two temperature measurements may be attributed to inaccuracies in the sensor calibration curve, however, more interestingly, it also shows a consistent increase in the sensor measurements with increasing exposure to hot combustion gases.

The increase in the resistance-based temperature measurement with increasing high temperature exposure can be explained by a change in the morphology of the polysilicon. Prolonged exposure to high temperature combustion gases produces a bias increase in the polysilicon resistance which dynamically shifts the sensor calibration curve upwards. Consequently, the longer the sensor is exposed to high temperature gases, the higher is its temperature reading. The change in the calibration curve also suggests that the sensor, as currently designed, is unusable in the high temperature environment of a micro-engine combustor.

In order to understand the increase in film resistance, and to identify a stable operating range for the sensor, patterned polysilicon films on thermal oxide were subjected to three different annealing experiments. These experiments were not intended to develop detailed mechanisms for high temperature polysilicon degradation; instead, they were only intended to see whether the behavior of the sensor was consistent with the reports of other researchers, and whether a stable operating regime for the sensor could be identified.

In experiment one, samples were progressively exposed to temperatures between 200 and 1000 °C for 4 h. The room temperature resistance of the igniter was measured after each run, and as shown in Fig. 8, remained stable until

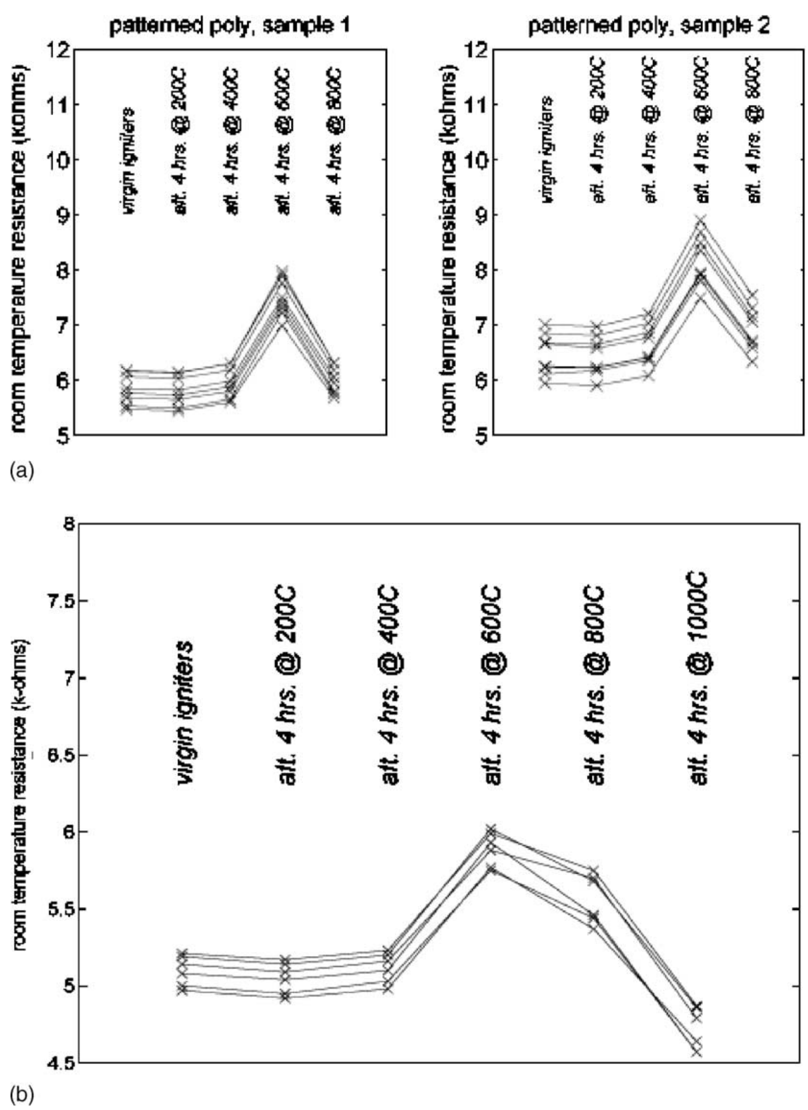
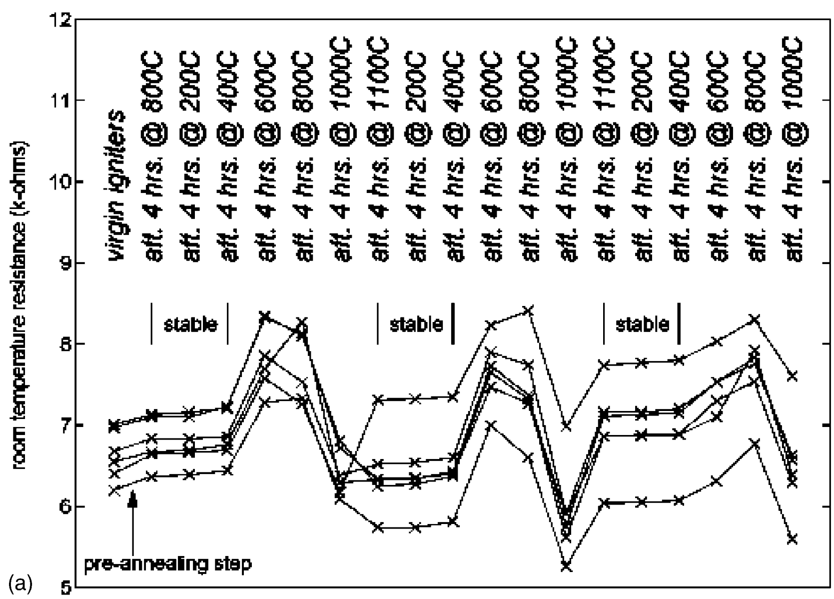


Fig. 8. Measurement of room temperature resistance of polysilicon igniters after progressive high temperature exposure, showing a rapid drop in the resistance after a 800 °C run: (a) air-ambient; (b) nitrogen-ambient. (Note: the different curves represent eight different igniters on a single chip.)

400 °C and then became non-linear after a 600 °C thermal anneal. The initial increase in resistance may be explained by changes in the concentration of electrically active dopant atoms. Phosphorus atoms are known to diffuse towards the grain boundaries and become electrically inactive [11–14]. This phenomenon is known as dopant atom segregation, and can increase polysilicon resistance due to a reduction in the concentration of active carriers. Since the dopant level of the polysilicon films considered herein (10^{20}/cm^3) exceeds the theoretical saturation values for temperatures up to 1100 °C [15,16], the films are in a super-saturated state after dopant diffusion. Therefore upon annealing, dopant atom segregation drives them towards equilibrium by reducing the concentration of active carriers, thereby causing the resistance to increase initially. Charge trapping effects are also known to cause an increase in resistance due to a reduction in the charge carrier concentration. However, since the 10^{12}/cm^3 sites available for charge trapping saturate at a negligible fraction of the total carrier concentration for heavily doped films, this effect is expected to be minimal for the films considered herein.

At higher temperatures, the increase in resistance due to dopant atom segregation is countered by the combined and dominating influence of two additional phenomenon. First, secondary grain growth with increasing temperatures [11,13,15] increases carrier mobility due to a decrease in



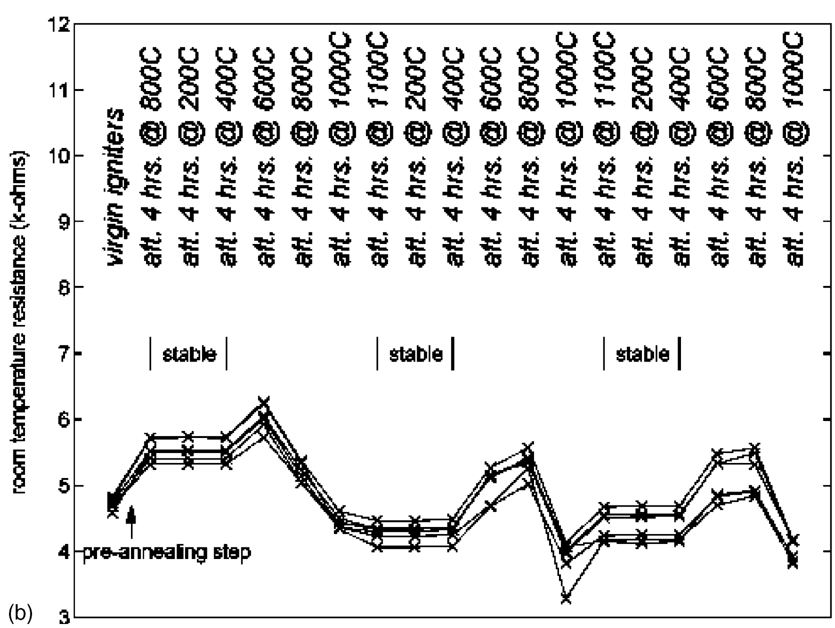


Fig. 9. Room temperature resistance measurements of a pre-annealed polysilicon resistor after progressive exposures to an inert high temperature environment: (a) poly + TEOS sample; (b) poly + thermal oxide sample.

grain boundary scattering [16]. Second, crystallographic relaxation proposed by Colinge et al. [11] partly removes grain boundary defects and increases the free carrier concentration at high temperatures. At higher temperatures, effects due to crystallographic relaxation and secondary grain growth begin to dominate, causing the resistance to decrease from thereon.

Experiment two was intended to see whether the sensor could be operated stably after an initial high temperature exposure of the type shown in Fig. 8, and to evaluate the effects of multiple annealing cycles. The results are plotted in Fig. 9, and show that the room temperature resistance of polysilicon following isochronal anneals settles into a cyclic pattern. Consistent with the observations of Makino and Nakamura [15], this suggests that the resistance is predominantly determined by a combination of the solid solubility limit and the carrier mobility at each annealing temperature, and is therefore uniquely and reversibly determined by the last annealing temperature.

Experiment three was intended to determine a stable operating regime for the sensor. The results plotted in Figs. 8 and 9 suggest that the resistance of the polysilicon is stable for several tens of hours as long as it is annealed below 600 °C. Additional tests actually showed that the resistance was barely stable up to 450 °C (Fig. 10(a)). With hopes to try and extend the operating range of the sensor, an

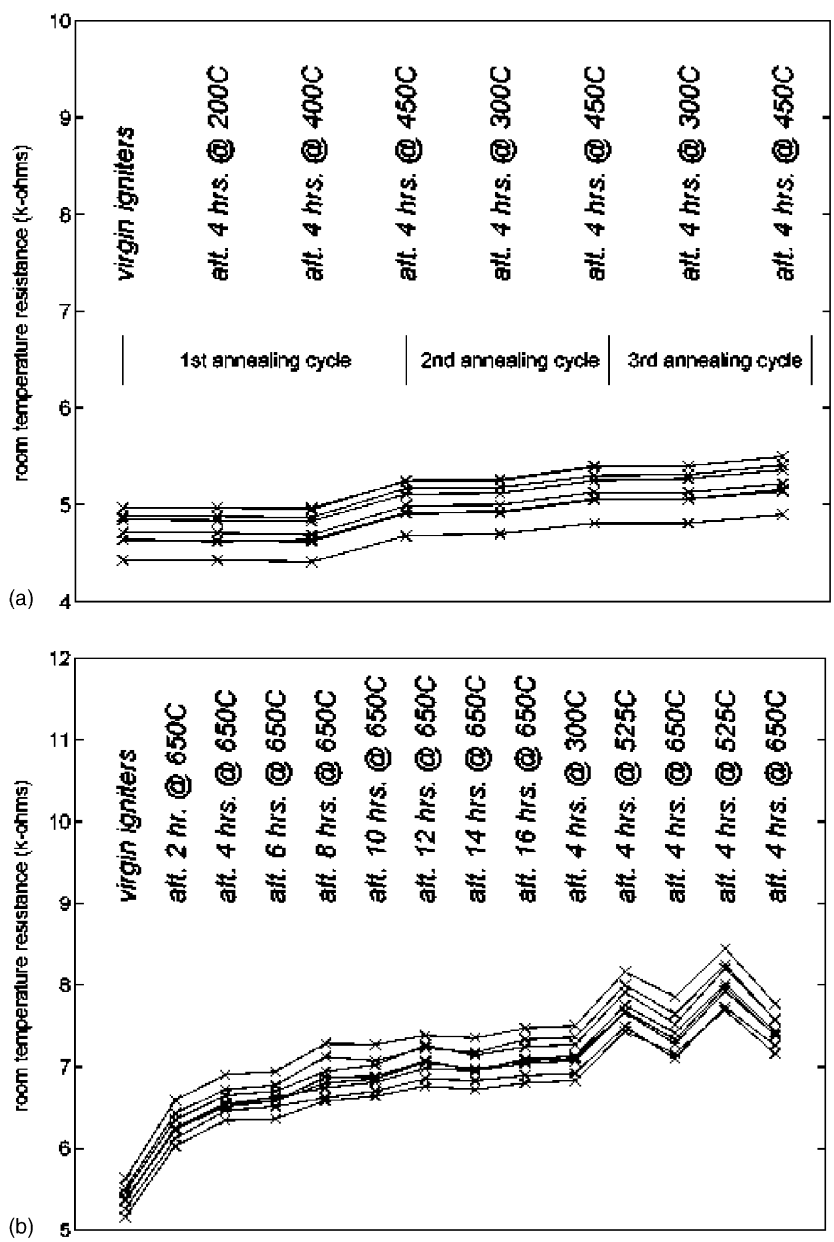


Fig. 10. Stability of the polysilicon resistance during repeated anneals up to 450 and 650 °C: (a) stable resistance up to 450 °C; (b) changed resistance after an initial annealing-to-equilibrium step at 650 °C.

attempt was made to stabilize carrier concentration at the highest annealing temperature at which resistance-reducing effects due to secondary grain growth and crystallographic relaxation have not yet set in. This temperature was empirically determined to be approximately 650 °C for these particular samples.

In order to stabilize the carrier concentration, the samples were sequentially annealed in a N_2 ambient at 650 °C until the resistance was observed to reach the equilibrium value; the results are plotted in Fig. 10(b). It is seen that even after the sensor has been pre-annealed to equilibrium at 650 °C, its resistance continues to reversibly change between equilibrium values at 525 and 650 °C, and is uniquely determined by the last annealing temperature in the 400–650 °C range.

5. Conclusions

This paper describes the development of micro-fabricated ''on-chip'' igniters and temperature sensors for the combustion system of the engine. The application of thin-film polysilicon resistive elements as igniters for the micro-engine combustor showed that it was possible to locally heat an isolated element up to 900 °C and ignite a combustible hydrogen–air mixture. Prior to their integration into the micro-engine combustor however, additional design changes are still needed to better insulate them from the supporting silicon substrate. The use of heavily doped polysilicon resistors as temperature sensors for the engine was also evaluated. The results suggested that a suitably calibrated sensor may be used in some of the cooler sections of the micro-engine combustor up to temperatures of 400 °C. This range is primarily limited by complex resistivity changes due to charge segregation, secondary grain growth and crystallographic relaxation effects that rendered the sensor difficult to calibrate.

Acknowledgements

The authors are grateful to Professors Martin Schmidt, Alan Epstein and Stephen Senturia for their insightful suggestions, to Paul Warren for help with the experiments, to Kurt Broderick for help during the micro-fabrication, and to all the other members of the MIT micro-engine team for their help and support. This work was largely supported by ARO, Dr. R. Paur technical manager, and by DARPA, Dr. S. Wilson technical manager. All devices were fabricated at the MIT Microsystems Technology Laboratories; the support of the technical staff is gratefully acknowledged.

References

[1] Epstein, et al., Micro-heat engines, gas turbines, and rocket engines—the MIT microengine project, in: Proceedings of the 28th AIAA Fluid Dynamics and Fourth AIAA Shear Flow Control Conference, Snowmass Village, CO, June 29–July 2, 1997.

[2] S.A. Jacobson, Aerothermal challenges in the design of a microfabricated gas turbine engine, in: Proceedings of the 29th AIAA Fluid Dynamics Conference, Albuquerque, NM, June 15–18, 1998.

[3] L.G. Frechette, S.A. Jacobson, K.S. Breuer, F.F. Ehrich, R. Ghodssi, R. Khanna, C.W. Wong, X. Zhang, M.A. Schmidt, Demonstration of a microfabricated high-speed turbines supported on gas bearings, in: Proceedings of the Technical Digest of the Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, June 4–9, 2000, pp. 43–47.

[4] A. Mehra, A.A. Ayon, I.A. Waitz, M.A. Schmidt, Mirofabrication of high temperature silicon devices using wafer bonding and deep reactive ion etching, J. Microelectromech. Syst. 8 (2) (1999) 152–160.

[5] A. Mehra, X. Zhang, A.A. Ayon, I.A. Waitz, M.A. Schmidt, C.M. Spadaccini, A six-wafer combustion system for a silicon micro gas turbine engine, J. Microelectromech. Syst. 9 (4) (2002) 517–527.

[6] A. Mehra, X. Zhang, A.A. Ayon, I.A. Waitz, M.A. Schmidt, Through-wafer electrical interconnect for multilevel microelectromechanical system devices, J. Vac. Sci. Technol. B 18 (5) (2000) 2583–2589.

[7] S.L. Firebaugh, K.F. Jensen, M.A. Schmidt, Investigation of high temperature degradation of platinum thin films with an in-situ resistance measurement apparatus, J. Microelectromech. Syst. 7 (1) (1998) 128–135.

[8] J.M. Poate, K.N. Tu, J.W. Mayer (Eds.), Thin Films—Interdiffusion and Reactions, Silicide Formation, The Electrochemical Society, Inc., 1978, Chapter 10, p. 378.

[9] E.I. Cole, J.S. Suehle, K.A. Peterson, P. Chaparala, A.N. Campbell, E.S. Snyder, D.G. Pierce, OBIC analysis of stressed, thermally-isolated polysilicon resistors, in: Proceedings of the 1995 IEEE International Conference on Reliability Physics, Las Vegas, NV, April 3–6, 1995, pp. 234–243.

[10] S. Wessel, M. Parameswaran, S.R. Morrison, R.F. Frindt, A CMOS thermally-isolated heated structure as a substrate for semiconductor gas sensors, Electron. J. 23 (6) (1992) 451–456.

[11] J.P. Colinge, E. Demoulin, F. Delannay, M. Lobet, J.M. Temerson, Grain size and resistivity of LPCVD polycrystalline silicon films, J. Electrochem. Soc. 128 (9) (1981) 2009–2014.

[12] E. Loh, Interpretation of DC characteristics of phosphorus-doped polycrystalline silicon films: conduction across low-barrier grain boundaries, J. Appl. Phys. 54 (8) (1983) 4463–4466.

[13] M.M. Mandurah, K.C. Saraswat, Phosphorus doping of low pressure chemically vapor-deposited silicon films, J. Electrochem. Soc. 126 (6) (1979) 1019–1023.

[14] J. Murota, T. Sawai, Electrical characteristics of heavily arsenic and phosphorus doped polycrystalline silicon, J. Appl. Phys. 53 (5) (1982) 3702–3708.

[15] T. Makino, H. Nakamura, Resistivity changes of heavily-boron-doped CVD-prepared polycrystalline silicon caused by thermally annealing, Solid-State Electron. 24 (1981) 49–55.

[16] S. Solmi, M. Severi, R. Angelucci, L. Baldi, R. Bilenchi, Electrical properties of thermally and laser-annealed polycrystalline silicon films heavily doped with arsenic and phosphorus, J. Electrochem. Soc. 129 (8) (1982) 1811–1818.