INVESTIGATING THE APPLICATIONS OF SILICON AND SiGe ALLOYS TO ENERGY HARVESTING

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Annotatsiya: Kremniy (Si) va kremniy-germaniy (SiGe) qotishmalari energiya yig'ishda yuqori samaradorligi bilan ajralib turadi. Ushbu maqolada Si va SiGe materiallarining fizik va elektron xususiyatlari, shuningdek ularning fotovoltaik qurilmalardagi qo'llanilishi tahlil qilinadi. SiGe qotishmalari kengroq diapazonda nurlanishni yutish imkonini berib, energiya yig'ish samaradorligini oshiradi. Shuningdek, bu materiallarning termal barqarorligi va ishlab chiqarish texnologiyalari haqida ham batafsil ma'lumotlar taqdim etiladi. Tadqiqot natijalari Si hamda SiGe asosidagi qurilmalar orqali energiya yig'ishda amaliy qo'llanilish imkoniyatlarini kengaytirishga qaratilgan, bu esa ularni quyosh energiyasi sanoatida muhim komponentga aylantiradi. Mazkur maqola soha mutaxassislari va ilmiy tadqiqotchilar uchun foydali axborot manbai hisoblanadi.

Kalit so'zlar: kremniy (Si), kremniy-germaniy (SiGe) qotishmalari, energiya yig'ish, fotovoltaik materiallar, quvvat o'tkazuvchanligi, quyosh batareyalari, termal barqarorlik, elektron xususiyatlar, energiya samaradorligi, yangi materiallar.

Аннотация: Сплавы кремния (Si) и кремний-германия (SiGe) характеризуются высокой эффективностью сбора энергии. В данной статье анализируются физические и электронные свойства материалов Si и SiGe, а также их применение в фотоэлектрических устройствах. Сплавы SiGe позволяют поглощать излучение в более широком диапазоне, повышая эффективность сбора энергии. Также представлена подробная информация о термической стабильности и технологиях производства этих материалов. Результаты исследования направлены на расширение возможностей практического применения в области сбора энергии с помощью устройств на основе Si и SiGe, что делает их важным компонентом солнечной энергетики. Данная статья представляет собой полезный источник информации для специалистов и исследователей отрасли.

Ключевые слова: кремний (Si), сплавы кремния с германием (SiGe), сбор энергии, фотоэлектрические материалы, передача энергии, солнечные элементы, термостабильность, электронные свойства, энергоэффективность, новые материалы.

Annotation: Silicon (Si) and silicon-germanium (SiGe) alloys are characterized by high efficiency in energy harvesting. This article analyzes the physical and

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electronic properties of Si and SiGe materials, as well as their applications in photovoltaic devices. SiGe alloys allow for the absorption of radiation in a wider range, increasing the efficiency of energy harvesting. Detailed information on the thermal stability and manufacturing technologies of these materials is also provided. The results of the research are aimed at expanding the possibilities of practical applications in energy harvesting through Si and SiGe-based devices, which makes them an important component in the solar energy industry. This article is a useful source of information for industry professionals and researchers.

Keywords: silicon (Si), silicon-germanium (SiGe) alloys, energy harvesting, photovoltaic materials, power transfer, solar cells, thermal stability, electronic properties, energy efficiency, new materials.

Introduction.

Very few are the applications of silicon itself as a thermoelectric material as of its low ZT. However, its alloys with Ge (meant to decrease its thermal conductivity)have been (and still are, to a large extent) the reference material for many key applications of thermoelectricity. On one side, SiGe thin films provide ways of easy on-chip integration of a TEG. On the other hand, Si—Ge alloys have been extensively used as massive legs in radioisotope thermoelectric generators (RTGs) to power deep-space probes. In this case, SiGe alloy shave been the natural choice as no mature materials able to sustain the high temperatures typical of this class of TEGs were available in the1970s.

Focusing onto integrated applications, most of the reported research has been aimed at developing TEG designs that coped with the relatively high thermal conductivity of the material to compensate for the relatively low conversion efficiency. Achieving large heat current sand minimal thermal shunts could actually make output power densities competitive with those obtainable with high-ZT standards. A good example of such an approach comes from a series of papers published by the Infineon Labs over the first years of 2000. The major problem with integrated TEGs is actually that of forcing the heat flow through planar elements that are oriented normal to the thermal gradient. Decoupling the thermal vias from the (bulk) substrate could be achieved by opening cavities under the TEG elements (Figure 4.10) [27]. In this way the wafer could be used as the thermal contact to the heat sink. This, coupled with a proper choice of the dop-ing level of the substrate, allowed to minimize the otherwise large reduction of the temperature difference actually applied over the thermoelectric legs. For a front-to-back ΔT of 3 K an actual temperature drop of 1.7 K was estimated to occur over the thermoelectric leg. In addition, the reduced thermal shunt enabled a relatively large heat flow through the device legs that compensated for the low ZT and the small ΔT (that further reduced the conversion efficiency), so that an output power density

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of≈5μW/cm^2 could be attained when applying a temperature difference over the chip as small as10K.

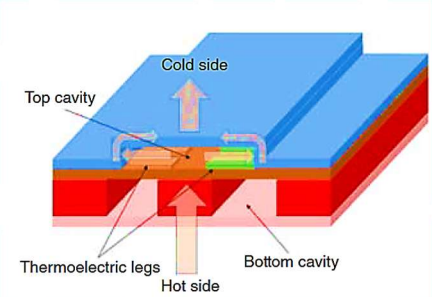


Figure 1. Comparison of the layouts of the on-chip TEG developed.

LITERATURE REVIEW.

Key Literature Sources and Their Analysis Sze, S. M. "Semiconductor Devices: Physics and Technology", 3rd Edition, Wiley, 2007 this book provides a comprehensive explanation of silicon and its fundamental properties. It covers the electronic and thermal characteristics of silicon, emphasizing its role in energy conversion processes, the work offers detailed insights into silicon-based photovoltaic cells and methods to enhance their efficiency [1]. And also Rowe, D. M. "Thermoelectrics Handbook: Macro to Nano", CRC Press, 2005 this handbook presents extensive information on thermoelectric materials, including SiGe alloys. It discusses the electrical and thermal properties of SiGe alloys and evaluates their thermoelectric performance, highlighting their advantages in thermoelectric generators and waste heat recovery systems [2]. Cahill, D. G., et al. "Nanoscale thermal transport", Journal of Applied Physics, 93(2), 2003, focuses on heat transport at the nanoscale, including silicon and SiGe nanolayers, the study is vital for improving the energy efficiency of micro- and nanoelectronic devices by controlling thermal conductivity in these materials [3]. Dresselhaus, M. S., et al. "New Directions for Low-Dimensional Thermoelectric Materials", Advanced Materials, 19(8), 2007. Explores advancements in thermoelectric properties of silicon- and SiGe-based low-dimensional structures. The paper presents innovative approaches to enhance energy conversion efficiency using nanoscale architectures [4]. Nolas, G. S., Sharp, J., Goldsmid, H. J. "Thermoelectrics: Basic Principles and New Materials Developments", Springer, 2001. Discusses a broad range of thermoelectric materials with emphasis on SiGe alloys [5]. The book details their application in thermoelectric generators and coolers, providing key technical parameters and material advantages.

Based on the reviewed literature, silicon and silicon-germanium alloys play a critical role in energy-related technologies, particularly in thermoelectric and photovoltaic applications. SiGe alloys stand out for their superior thermoelectric efficiency, enabling effective conversion of heat to electrical energy. Silicon's abundance, environmental friendliness, and ease of integration into existing

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technologies make it a cornerstone material for solar energy harvesting and semiconductor devices. Recent research is increasingly focusing on nanoscale engineering of these materials to further boost their performance.

A different design was developed by Xie using a fully CMOS-compliant fabrication process in a Ge-free thermoelectric device. A double set of cavities was generated to force heat to flow through p- and n-legs lying parallel to the substrate. Heat was then injected from the substrate, forced to flow parallel to it over a membrane sustaining the thermoelectric elements and then dissipated through a vacuum-insulated thermal collector. An output power density of 1.5 $\mu W/cm^2$ over a ΔT of 5 K was reported, a value mostly limited by the relatively large electrical resistance associated to the micrometric size of the contact pads. Use of suspended legs in microharvesters was proposed by Leonov and coworkers at IMEC. Hole- and electron-doped SiGe films were deposited onto sacrificial trapezoidal SiO_2 blocks that were shaped by using a photoresist mask with variable thickness along with a focus energy matrix. Beveled walls helped deposit the active layers. At the process end, SiO_2 blocks were wet-etched away leaving an Al-contacted p–n series the hot side of which was separated from the substrate by 6 μm. Power density was measured to be ≈1 $\mu W/cm^2$ for ΔT = 5 K, mostly limited by local failures (short- and open-circuits) within the chip.

An even more radical approach to minimize thermal shunts was pursued by Yu and co-worker. In their layout, thermoelectric legs were bridging fully separated blocks in a comb structure. After deposition of an interdigitated p–n Si series (lying flat onto the substrate) the comb was realized by deep RIE from the back, with the thermoelectric legs lying across the substrate fingers. The temperature difference could then be applied to the two blocks, ensuring heat to flow almost entirely through the thermoelectric legs. Since the only possible shunt was the radiative coupling between the hot and cold blocks, a large thermal current could be converted into electric power. Also, large temperature differences could be applied without losses from direct thermal coupling between the hot and cold sink. A very large power density of about 100 $\mu W/cm^2$ for a ΔT of 30K was measured, apparently a huge value compared to Leonov's results of 6.4 $\mu W/cm^2$ upon application of the same ΔT.

METHODOLOGY.

Although enhanced thermoelectric properties of SiNWs have been demonstrated, the introduction of these structures into a practical device is still challenging. To avoid power losses it is mandatory an optimal arrangement of the nanowires between hot and cold sinks, and a perfect electrical connection [6]. Setting a bridge between nanostructures and macroscopic world requires precise manufacturing as the one that can be provided by silicon micromachining

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processes. Commonly, top-down platforms embedding bottom-up NWs are required. However, bottom-up NW growing methodology can be interesting in order to achieve a higher density of nanowires and increase the volumetric power [7]. Two main obstacles have to be solved for the application of these approaches [8]. First, it is important to restrict the area where the NW will grow to the active part of the device. Second, long distances between hot and cold parts have to be provided in order to avoid thermal shunts by convection or radiation. A proof-of-concept of a thermoelectric micro-generator using VLS nanowire growth was proposed by Davila et Figure 2 shows a sketch of the device. Silicon p-doped nanowires were grown in a silicon micro machined device, contacting a suspended platform with the bulk of the chip. In a harvesting scenario, the device is put in contact with a hot surface. The low thermal mass of the platform allows for a rapid cooling compared to bulk, providing the necessary temperature difference for generating power. A series of heaters/thermometers and metal pads allowed to control and measure heat while extracting the generated current. In order to achieve a long separation between hot and cold parts, a series of micro spacers were introduced that remained suspended in the final prototype, held by the NWs array. A distance of 90 μm was achieved between the walls. The gold catalyst particles were deposited by means of galvanic displacement, a selective method that allowed introducing the seeds only in the Si exposed surfaces. With this configuration, a power density close to 1.5 mW/cm^2 was demonstrated by providing a temperature difference of 300°C.

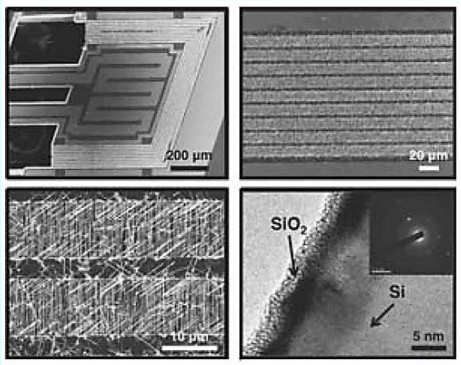


Figure 2. Images of the resulting prototypes, showing details of the nanowire growing regions and nanowire structure.

RESULTS.

Constraints acting on the conversion efficiency of top-down nanowire-based TEGs will be illustrated with reference to the typical structure of a lateral TEG as the one sketched. The device is made of thermos elements with complementary doping (alternating n- and p-type) composed by a large number of stacked nanowire sin parallel, that are connected in order to create a sufficient number of thermocouples in series. In the figure, the polycrystalline stacked nanowires described in the previous section have been utilized in the TEG by way of example–

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although the use of other types of nanowires with in the same structure is also possible. During operation, the thermal flow in the TEG is as represented. The device is used in contact with a hot surface at a temperature, larger than the ambient temperature Ta. As a result, a thermal flow is built up across the device that gives rise to a temperature difference across the nanostructured thermocouples. Being ΔT the temperature difference, the power P transfer red to an electrical load in matching conditions by the TEG can be written as

$$P = \frac{(n_{tp} S_{pn} \Delta T)^2}{4R_{tp}}$$

where S_{pn} is the overall Seebeck coefficient of the individual p–n nanostructured thermocouple composed by complementarily doped nanowire sin the device, n_{tp} is the number of thermocouples connected in series in the device, and R_{tp} is the overall electrical resistance of such thermocouple chain. Equation the formula clearly shows that in order to obtain a high conversion power it would be desirable to increase as much as possible the temperature difference ΔT in the device and to keep R_{tp} low. Both parameters actually depend on the design of the TEG, since the thermal behavior of the device can be schematically modeled by the series connection of two thermal resistances. In the model, R_{Tdev} represents the overall thermal resistance of the device, whereas R_{Trad} is the thermal resistance between the device and the surrounding environment and Tc is the temperature of the cold contact of the thermocouples. In case a dissipater is utilized on the TEG. From the model, the temperature difference ΔT in the TEG computes to

$$\Delta T = T_h - T_c = (T_h - T_a)\frac{R_{Tdev}}{R_{Tdev} + R_{Trad}}$$

Thus, considering a given temperature difference between the hot surface and the environment, ΔT is enhanced if the thermal resistance of the device is comparable or even larger than that of the heat sink. This is actually not possible for typical TEGs, since the thermal resistance of heat sinks (particularly in natural convection regime, which is almost always the case of interest for TEGs) is always higher than that achievable with the device. Moreover, the thermal resistance of the device cannot be increased indefinitely, since its electrical resistance would increase as well because of physical and geometrical constraints. For instance, the thermal resistance of the device maybe increased by designing longer thermos elements, but this will also increase their electrical resistance and therefore R_{tp} in equal this formula. Moreover, it must be kept in mind that R_{Tdev} is the overall thermal resistance of the device, and not that of then a no wires only, and therefore includes the effect of other material sin the TEG, such as the Si_3N_4/SiO_2 dielectric membrane or the silicon anchors on the suspended mass and, more importantly, the

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effect of thermal exchange though air to ward the surrounding environment and the hot surface. Given such constraint sand the properties of the materials employed in the TEG, an optimum design can be achieved starting from the characteristics of the chosen heat sink. In this optimization procedure, quite obviously, the availability of nanowires with low thermal conductivity and electrical resistivity will be of help to reach good conversion performances.

CONCLUSION.

This study highlights the significant potential of silicon (Si) and silicon-germanium (SiGe) alloys in the field of energy harvesting. Due to their favorable electronic properties, thermal stability, and mature fabrication technologies, these materials offer promising opportunities for efficient thermoelectric and photovoltaic applications. Silicon, being abundant and well-understood, serves as a reliable base material, while SiGe alloys provide enhanced thermoelectric performance through improved carrier mobility and reduced thermal conductivity. The integration of SiGe materials in energy harvesting devices can lead to higher conversion efficiencies and broaden the scope of renewable energy solutions. Future research focusing on optimizing the composition, nanostructuring, and device architecture of these materials will be crucial in overcoming existing limitations and unlocking their full potential in sustainable energy technologies. Moreover, advancements in nanotechnology and material engineering have opened new avenues to tailor the properties of Si and SiGe alloys at the nanoscale, thereby optimizing their energy conversion characteristics. By engineering nanostructures such as quantum wells, nanowires, and superlattices, researchers can further reduce thermal conductivity without compromising electrical conductivity, which is critical for enhancing thermoelectric efficiency.

Despite these promising aspects, challenges such as material cost, long-term stability, and scalability of production need to be addressed before widespread commercial application. Continued interdisciplinary research combining materials science, device engineering, and system integration is essential to develop practical and cost-effective energy harvesting solutions based on Si and SiGe alloys. Si and SiGe alloys stand as key materials in paving the way towards more efficient and sustainable energy harvesting technologies. Their unique properties coupled with ongoing technological advancements make them strong candidates for future energy systems, contributing to global efforts in renewable energy development and environmental preservation.

REFERENCES

1. Sze, S. M. (2007). Semiconductor Devices: Physics and Technology (3rd ed.). Wiley.

ISSN 3030-3907

2. Rowe, D. M. (Ed.). (2005). Thermoelectrics Handbook: Macro to Nano. CRC Press.
3. Cahill, D. G., Ford, W. K., Goodson, K. E., Mahan, G. D., Majumdar, A., Maris, H. J., Merlin, R., & Phillipis, S. R. (2003). Nanoscale thermal transport. *Journal of Applied Physics, 93*(2), 793–818. https://doi.org/10.1063/1.1524305
4. Dresselhaus, M. S., Chen, G., Tang, M. Y., Yang, R. G., Lee, H., Wang, D. Z., Ren, Z. F., Fleurial, J. P., & Gogna, P. (2007). New directions for low-dimensional thermoelectric materials. *Advanced Materials, 19*(8), 1043–1053. https://doi.org/10.1002/adma.200601376
5. Nolas, G. S., Sharp, J., & Goldsmid, H. J. (2001). Thermoelectrics: Basic Principles and New Materials Developments. Springer.
6. Kim, W., & Majumdar, A. (2006). Thermoelectric nanocomposites with high figure of merit. Microscale Thermophysical Engineering, 10(2), 215-224. https://doi.org/10.1080/10893950600786433
7. Zhu, T., & Otsuka, A. (2013). Advances in silicon and SiGe thermoelectric materials. Materials Science and Engineering: R: Reports, 73(2), 75-88. https://doi.org/10.1016/j.mser.2012.09.001
8. Sootsman, J. R., Chung, D. Y., & Kanatzidis, M. G. (2009). New and old concepts in thermoelectric materials. Angewandte Chemie International Edition, 48(46), 8616-8639. https://doi.org/10.1002/anie.200900598

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