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Exploration of Solar Cell Materials for Developing Novel PUFs in Cyber-Physical Systems

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Abstract Internet of Things (IoT) devices can be considered a significant component within cyber-physical systems. They can provide network communication in addition to controlling the various sensors and actuators that exist within the larger cyber-physical system. IoT devices tend to be small and contain a limited battery supply. They typically have strict constraints placed on their power consumption and available hardware resources. It is for these reasons that energy-efficiency is a major consideration in the design of these resource constrained devices. In addition, these devices are often deployed in unsecured locations which raises concerns about the security of the device. However, the limited amount of available resources presents an obstacle towards the implementation of security protocols for these cyber-physical systems. Physically Unclonable Functions (PUFs) show promise as a potential security option. PUFs can help provide protection from issues such as IC piracy, counterfeiting, etc. Furthermore, solar cells have been utilized as a power source in IoT devices. In this paper, we propose a novel solar cell based PUF that leverages the intrinsic variations present in solar cells. As a proof of concept, we have constructed multiple copies our proposed solar cell based PUF using amorphous silicon, monocrystalline silicon, and polycrystalline solar cells. The reliability and uniformity of the responses produced by the copies of the PUFs made from the different types of solar cells were evaluated against variations in temperature and light intensity. From our experiments, we found that with respect to temperature the range of average reliability values was 84.41% to 91.20% and the range of average uniformity values was 49.34% to 51.26%. With respect to light intensity, the range of average reliability values was 95.45% to 97.75% and the range of average uniformity values was 48.74% to 52.81%. In addition, Monte Carlo simulations performed on monocrystalline silicon resulted in a uniqueness value of 49.989%.

Keywords Physically Unclonable Function (PUF) · Cybersecurity · Security · Solar Cell · IoT.

1 Introduction

Cyber-physical systems consist of the integration of cyber and physical components. They typically use a combination of sensors, actuators, processing units, and communication via a network. IoT devices tend to be a significant component of cyber-physical systems as they can provide the network communication capabilities in addition to directly interfacing with the sensors and actuators. Due to being a key component, any IoT specific security issues should prove just as concerning for the cyber-physical system as a whole [10].

The Internet of Things (IoT) consists of a network of Internet connected devices that have the ability to transmit information as part of their use in intelligent applications [6]. These cyber-physical systems offer quality of life improvements by allowing physical objects to be directly integrated with the digital world. The number of IoT devices in the market continues to grow and is expected to eclipse 50 billion connected devices by 2021 [20]. In general, IoT devices tend to be small and contain a limited battery supply. As a result, these devices are typically subjected to strict constraints on their power consumption and available hardware resources [1].

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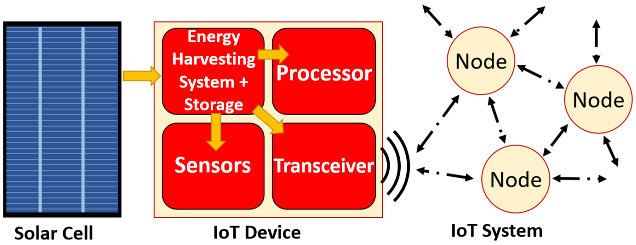


Fig. 1 Example of integration of solar cells within an IoT system

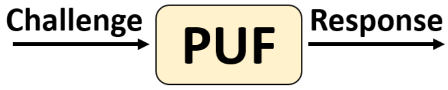


Fig. 2 Example of PUF operation

Energy harvesting is one technique that shows some promise as a way to improve energy efficiency [15]. Among the various energy harvesting technologies, the use of solar cells to harvest solar energy provides the highest power density. They are therefore an ideal choice for powering IoT devices as shown in Fig. 1 [19]. Highly efficient solar cells could even prove to be a viable option for indefinitely powering an IoT device without requiring a battery replacement. One such example is the Gallium Arsenide (GaAs) solar cell developed by Alta Devices which has an efficiency of 28.8% [30]. The integration of cells such as these could drastically increase the amount of time an IoT device can operate without needing a battery replacement, or even completely eliminate the need to replace the battery.

IoT devices also face major challenges in the form of security. Two major areas of concern are authentication and access control [21],[14]. The non-volatile memories used to store secret keys have been shown to be vulnerable to active attacks [3], [17]. Furthermore, it may be too expensive in terms of cost and energy to introduce high level security through the addition of tamper resistant circuitry.

Physically Unclonable Functions (PUFs) have drawn interest as a hardware security primitive that could be more specially suited for integration in resource constrained devices. PUFs have been shown to address a variety of security concerns such as IC piracy, counterfeiting, etc. [25]. They can be used in cyber-physical security and IoT devices as a major component in protocols for secure authentication and key management [2] [26] [22].

As shown in Fig. 2, the input to a PUF is called a "challenge" and the associated output is called a "response". For a given challenge, each copy of an ideal PUF would produce a unique response. This is due to the fact that the response of each PUF is tied to uncontrollable intrinsic variations that are caused by the IC manufacturing process. These variations are uncontrollable and thus unpredictable. In a way, a PUF can be considered as something of a fingerprint for CMOS ICs.

1.1 Motivation

PUFs are a type of circuit which utilize intrinsic variations introduced during the manufacturing process to create devices that are unique and unclonable. PUFs are commonly based on CMOS ICs which require dedicated hardware to function correctly. This dedicated hardware results in additional costs in terms of hardware and power consumption. In recent years, IoT devices have begun incorporating solar cells for tasks such as power generation and sensing. The goal of this work is the creation of a PUF whose integration with IoT devices would incur a minimal cost in the form of additional hardware. The use of solar cells provides the potential for a PUF that can be used as a source of power in addition to security. Solar cells are already a common power source in many remote applications and locations such as satellites, roadside displays, building rooftops, etc. By finding a way to leverage these existing components one could add security features without having to add any additional hardware. The cells' main purpose would be powering the device, but they would have the added advantage of also being able to be used as a method of providing security features. Our proposed design should be considered an energy harvesting based PUF and to the best of our knowledge is the first work to perform extensive testing on different types of solar cells to evaluate their viability for creating PUFs for cyber-physical systems.

1.2 Contributions of the Paper

In this work, we propose a novel PUF architecture based on solar cells. The proposed design utilizes a microcontroller to read the open-circuit voltages (V_{oc}) of a selection of solar cells and generate an associated response. The proposed design was implemented using amorphous silicon solar cells, monocrystalline solar cells, and polycrystalline solar cells. Furthermore, we evaluated the reliability and uniformity for each type of PUF against variations in temperature and variations in light intensity. We also performed uniqueness testing on monocrystalline silicon solar cells via Monte Carlo simulations.

1.3 Organization of the Paper

In Section II we provide information on PUFs and solar cells. Section III covers our proposed design methodology including the underlying architecture. Section IV presents the implementation details of our proposed design including information on each type of solar cell that was used. Section V describes the various types of testing and provides the results. Section VI provides a more in-depth discussion of the results including an analysis of each PUF's relative performance. Section VII gives conclusions and offers avenues for potential future work.

2 Background

2.1 Physically Unclonable Functions

PUFs are a type of circuit which utilize intrinsic variations introduced during the manufacturing process to create devices that are unique and unclonable. PUFs could serve as a solution to security problems such as IC piracy, counterfeiting, etc. [25] as their inability to be cloned would allow for the unambiguous identification of valid devices. Furthermore, they can be used in cyber-physical security and IoT devices as a major component in protocols for secure authentication and key management [2] [26] [22]. Silicon based PUFs such as arbiter PUF [8], Ring Oscillator (RO) [25], SRAM PUF [11] have proven to be very popular. These types of PUFs utilize transistor level variations to generate unique responses.

2.2 Solar Cells

Solar cells are known for their ability to convert energy from a light source into electricity with a relatively high conversion efficiency. They can serve as a nearly permanent source of power with low operating costs while also being virtually free of pollution. Solar cells generate both voltage and current. This is accomplished by using absorbed light to raise electrons to a higher energy state which can then be transported into an external circuit. The separation of photo-generated electrons and holes is achieved through the use of p-n junctions constructed from semiconductor and inorganic-organic materials (Fig. 3). It has been demonstrated that the incorporation of solar cells can improve the energy efficiency of IoT devices [29] and by extension improve the energy efficiency of cyber-physical systems which contain IoT devices. Other researchers have performed preliminary investigations on designing PUFs based on solar cells [24] [5] [16]. However, either those explorations weren't fully formed or the responses produced by those designs were directly tied to the current light intensity. This should prove a major hindrance towards their implementation in IoT devices as the light intensity of the operating environment is not typically something that can be easily modulated.

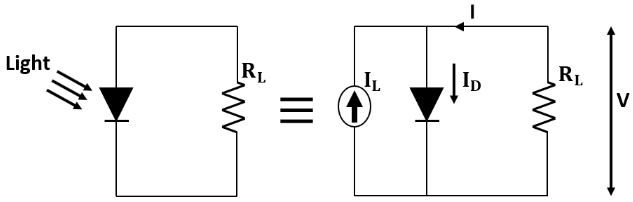


Fig. 3 Solar cell equivalent circuit

3 Methodology

The first step in designing a PUF based on solar cells is to choose an appropriate electrical parameter of the solar cells that will serve as the basis for ultimately generating a response. We believe that choosing a parameter that has a predictable relationship with changes in environment operating conditions will ultimately result in a more reliable PUF. In this section, we discuss our chosen solar cell electrical parameter that forms the basis of our proposed PUF.

3.1 Parameters to Design Solar Cell PUF

Perhaps the two most important electrical parameters of solar cells are their open circuit voltage (V_{oc}) and their short circuit current (I_{sc}). Both of these quantities are easily measurable and are fundamentally related through the current-voltage (I-V) equation of a solar cell [29]. That equation can be seen below:

$$I = I_0[exp(\frac{qV}{\eta kT}) - 1] - I_L \tag{1}$$

where I_0 is the reverse saturation current, q is the electron's charge, η is the diode ideality factor, k is the Boltzmann constant, T is the temperature, and I_L is the light generated current. V_{oc} is the maximum voltage that can be generated by a solar cell and it occurs when the current $I = 0$. Similarly, I_{sc} is the largest current that the cell can produce and is directly dependent on the spectrum of the incident light, i.e. the number of photons and the quantum efficiency of the solar cell. The previous equation can be rewritten as follows:

$$V_{oc} = \frac{\eta kT}{q} ln(\frac{I_L}{I_0} + 1) \tag{2}$$

This equation can be used to directly relate I_{sc} and V_{oc}, because in an ideal situation I_{sc} is equal to I_L. As demonstrated in the above equation, the value of V_{oc} for a solar cell is the direct result of the light generated current I_L and the reverse saturation current I_0. However, I_0 actually has a much greater influence on the value of V_{oc} as I_L tends to have only small variations in value while I_0 can actually vary by orders of magnitude. This is because I_0 is itself dependent on many solar cell characteristics such as electron-hole recombination lifetimes, interface state density, defects and impurities, etc. As a result, this value can vary wildly even among cells that are otherwise "identically produced". This high degree of entropy actually makes it an ideal candidate to serve as the basis for designing a PUF. Unfortunately, the reverse saturation current is not a quantity that can be as easily measured by a PUF during normal operation and thus other parameters should be considered.

As previously explained and shown in Equation (2), I_0 is the only parameter that contributes to V_{oc} that is also known to show orders of magnitudes in variations. This means that any variations in I_0 should likewise manifest in V_{oc} which is far easier to measure than I_0. It is known that solar cells which should be otherwise identical, such as produced from the same batch, will actually display variations in their V_{oc} values due to intrinsic variations introduced during the manufacturing process. Furthermore, the V_{oc} values of solar cells are known to respond in a predictable manner when subjected to changes in both temperature (linear relationship) and light intensity (logarithmic relationship). We believe this predictability will result in a PUF that is able to generate reliable data in various operating conditions. It is for these reasons that we selected the open-circuit voltage (V_{oc}) as the solar cell parameter on which to base our proposed PUF design.

Solar cells have been constructed from a myriad of different elements. However, silicon has proven to be a very popular choice and therefore we chose to use silicon solar cells with our proposed solar cell based PUF design. Furthermore, we evaluated our proposed design using multiple types of silicon solar cells to determine their viability in different environmental conditions. The specific types of silicon solar cells used were Panasonic AM-1417CA amorphous silicon solar cells ($V_{oc} = 2.4V$), IXYS KXOB22-12X1F monocrystalline solar cells ($V_{oc} = 630mV$), and AOSHIKE micro solar panel polycrystalline silicon solar cells ($V_{out} = 2V$).

3.2 Proposed PUF Architecture

Through the photovoltaic effect, solar cells generate a voltage when they are hit by photons. These output voltages will actually vary between solar cells due to intrinsic variations introduced during the manufacturing process. Our proposed design uses a microcontroller with an ADC to first capture these output voltages and convert them to digital values. The PUF uses these values to generate a 128 bit response by comparing the voltages in a pre-determined pattern. Each bit in the generated response is a direct result of a comparison made between the output voltages from two different groups of solar cells. 128 bits was chosen since it is a commonly used response size and larger response sizes could require more solar cells to implement. Further explanation on the actual hardware and software portions of our proposed design can be found below in Section IV.

4 Implementation

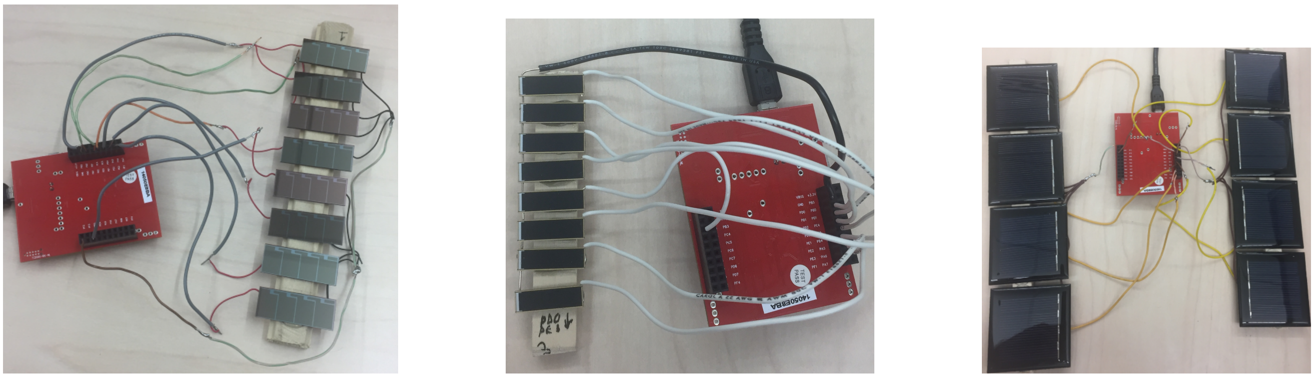
In this section, we present actual prototypes of our proposed solar cell based PUF. This section will highlight the various hardware (solar cells and microcontroller) and software components of our proposed design.

4.1 Hardware Components of Proposed PUF

Each prototype consists of 8 solar cells connected to ADC input pins on a microcontroller. A personal computer (PC) is used to communicate with the PUFs. In our implementations, we have used a selection of solar cells. The three types of solar cells were monocrystalline silicon, polycrystalline silicon, and amorphous silicon. A copy of each type of PUF is shown in Figure 4.

4.1.1 Amorphous Silicon Solar Cells

The amorphous cells used in our design were Panasonic AM-1417CA amorphous silicon solar cells [23]. Amorphous silicon cells do not have the regular atomic arrangements that are present in crystal silicon cells. This irregular atomic arrangement allows for more light absorption and thus certain types of amorphous silicon cells can be produced that have a film thicknesses of less than 1 μm [23]. The specific model we tested was designed for use in indoor applications such as wireless sensor networks, RF remote controls, battery chargers, etc. They have an open-circuit voltage (V_{oc}) of 2.4V with a max power of 18.75 μW. Table 1 provides a complete list of the electrical parameters of the amorphous silicon solar cells.



(a) Amorphous silicon PUF (b) Monocrystalline silicon PUF (c) Polycrystalline silicon PUF

Fig. 4 Prototype solar cell based PUFs

Table 1 Electrical Parameters of the Amorphous Silicon Solar Cells Used in our Experiments

Cell parameters	Typical ratings
Open-circuit voltage	2.4V
Short circuit current	13.5 μA
Max. power	18.75 μW
Voltage at max. power point	1.5V
Current at max. power point	12.5 μA

4.1.2 Monocrystalline Silicon Solar Cells

The monocrystalline cells used were the IXYS KXOB22-12X1F monocrystalline solar cells [13] which are used for various battery operated consumer products such as mobile phones, cameras, MP3 players, etc. These solar cells also have applications in IoT based devices such as wireless sensors, RFID tags, etc. These solar cells have very good response over a wide wavelength range and therefore can be used in a variety of indoor and outdoor applications. They have an open-circuit voltage (V_{oc}) of 630 mV with an efficiency of 22%. Table 2 provides a complete list of the electrical parameters of the monocrystalline silicon solar cells.

Table 2 Electrical Parameters of the Monocrystalline Silicon Solar Cells Used in our Experiments

Cell parameters	Typical ratings
Open-circuit voltage	630 mV
Short circuit current density	42.4 mA/cm^2
Max. peak power	18.6 mW/cm^2
Voltage at max. power point	501 mV
Fill factor	$\geq$ 70%
Solar cell efficiency	22%

4.1.3 Polycrystalline Silicon Solar Cells

Polycrystalline silicon solar cells are made of multiple silicon crystals. This differs from monocrystalline silicon solar cells where the entire cell is comprised of a single silicon crystal. Polycrystalline tends to have a cheaper manufacturing process than monocrystalline silicon. However, the existance of multiple crystals means they also tend to be less efficient. The polycrystalline silicon solar cells were AOSHIKE micro solar panel polycrystalline silicon solar cells. We were not able to find a data sheet for the cells. The information provided by their Amazon listing rates their peformance as an output voltage (V_{out}) of 2V and a current of 130 mA. They are a suitable power source in applications such as low-power electrical appliances, small motors, solar water pumps, lighting, etc. [4].

4.1.4 Microcontroller

Our proposed design requires using an ADC and a microcontroller to measure the solar cell output voltages. These voltage values are compared in a pre-determined pattern to generate a 128-bit response. Our example implementations (Figure 4) use a Tiva TM4C123GH6PM. We chose these as they have already been included in multiple applications such as network appliances and switches, remote monitoring, factory automation, etc. [12]. For testing purposes we use a PC to send challenges and receive responses via UART.

The ADC within that board is 12 bits. It should not necessarily be viewed as a requirement that other implementations must also use a 12-bit ADC. Our testing results from the next section will show that it is sufficient for creating a PUF. It is worth noting that changes in ADC resolution could cause differences in the results. At a minimum, other implementations should use an ADC with a high enough resolution that it is able to detect the voltage variations between each solar cell. Realistically a PUF is not going to have its ADC replaced so there is not a major concern on how changing the resolution would change the response. This would effectively be replacing the PUF in which case it is no longer expected to produce the same response. The exact effect, if any, that changing the ADC's resolution would have on the PUFs, we consider that to be outside the scope of our paper.

4.2 Software Components of Proposed PUF

The software running on the microcontroller is responsible for actually generating the PUF's response. The microcontroller must sample each connected solar cell through its ADC and then generate a response. For the actual comparison algorithm used to generate the response, we used the one described in [18]. Our implementation required accounting for the inherent noise in the ADC. This was done by averaging 16,000 readings per cell. The sampling rate was 125,000 samples per second and microcontroller speed was 20MHz. A PC was used to communicate via UART with the PUFs. This was mostly for testing purposes as it allowed us to easily record the generated responses.

5 Testing and Results

Reliability testing and uniformity testing were performed on three copies of each type of solar cell PUF. Both metrics were evaluated with respect to changes in temperature and changes in light intensity.

5.1 PUF Evaluation Metrics

The performance metrics on which we are evaluating our proposed PUF design are reliability and uniformity.

5.1.1 Reliability

The reliability of a PUF is a measure of how well it can reproduce a given response with respect to changes in a specified environment condition such as temperature. The reliability of a n-bit response can be calculated by the following equation:

$$Reliability = 100\% - \frac{1}{k}\sum_{i=1}^{k}\frac{HD(R_i, R'_{i,t})}{n} \times \% \qquad (3)$$

where HD denotes the hamming distance between a reference response R_i from PUF i and a separate response $R'_{i,t}$ from PUF i that has been generated under different environmental conditions. A total of k n-bit responses are generated under different environmental conditions in order to calculate the average hamming distance. The ideal reliability value is 100% which indicates that the PUF will always generate the correct response regardless of changes in its operating environment.

5.1.2 Uniformity

The uniformity is a measure of how balanced a PUF's response is in terms of the number of 1's and 0's. The ideal uniformity value is 50% which denotes that there are an equal number of 1's and 0's. Uniformity can be calculated by the following equation:

$$Uniformity = \frac{1}{n}\sum_{l=1}^{n} r_{i,l} \times 100\% \qquad (4)$$

where $r_{i,l}$ represents the l-th bit of response from PUF instance i.

5.1.3 Uniqueness

The uniqueness is a measure of how well a single PUF can be distinguished from the population as a whole. The ideal uniqueness value is 50% which effectively denotes that between any two PUF responses there is an equal probability that a given bit position between the responses will have unequal or equal values. It is calculated by using the following equation:

$$Uniqueness = \frac{2}{k(k-1)}\sum_{i=1}^{k-1}\sum_{j=i+1}^{k}\frac{HD(R_i, R_j)}{n} \times 100\% \qquad (5)$$

This equation effectively calculates the average hamming distance (HD) between every possible pair of PUFs in a population containing k total PUF copies. R_i and R_j are n-bit responses generated by PUF instances i and j, respectively such that $i \neq j$.

5.2 Testing with Respect to Temperature

A temperature chamber was used to evaluate the reliability of the generated responses over a range of temperatures from -20°C to 80°C. 25°C was used as the reference temperature for reliability testing and measurements were taken in increments of 5°C. A "LED-LENSER® V6 7732" was used to provide a constant source of light within the sealed testing chamber. The complete testing setup is shown in Figure 5.

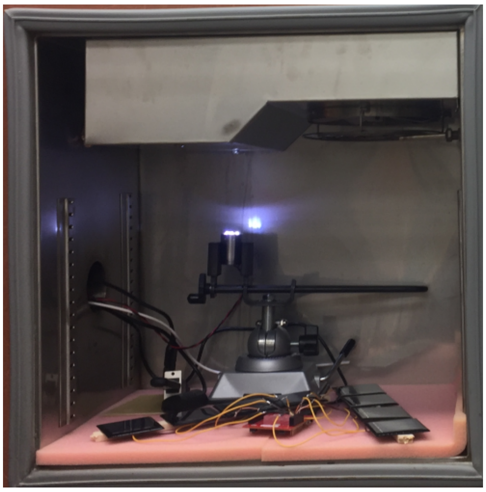


Fig. 5 Temperature testing chamber

5.2.1 Reliability Testing

Figure 6 shows the reliability values of the amorphous silicon PUFs and Table 3 shows the average reliability values for each copy of the PUF across the measured temperature range. The first copy of the PUF (PUF1) showed a remarkable consistency that manifested as an average reliability of 96.39%. However, this was an outlier as the other copies of the PUF did not fare nearly as well. There were pronounced drops in reliability as the temperature moved farther away from the reference value of 25°C and as a result overall average reliability was only 84.41%.

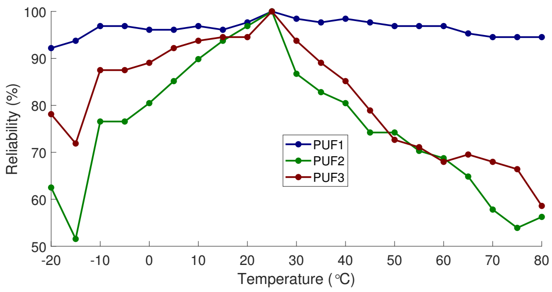


Fig. 6 Amorphous silicon reliability with respect to temperature

Figure 7 shows the reliability values for each of the monocrystalline silicon PUFs and Table 3 contains the average reliability for each copy of the PUF. The reliability of each copy of the PUF exhibited consistent changes as the temperature deviated from the reference value of 25°C and resulted in an overall average of 88.87%.

Figure 8 shows the reliability values for each of the polycrystalline silicon PUFs and Table 3 contains the average reliability for each copy of the PUF. The reliability values of the second and third copies of the PUF (PUF2 and PUF3) showed consistent behavior across the range of temperatures measured. PUF1 displayed similar reliability values for temperatures up to 50°C. Beyond that temperature the device demonstrated a notable drop in reliability that did not occur in the other copies of the PUF. Despite this, the PUFs still produced an overall average reliability of 91.20%.

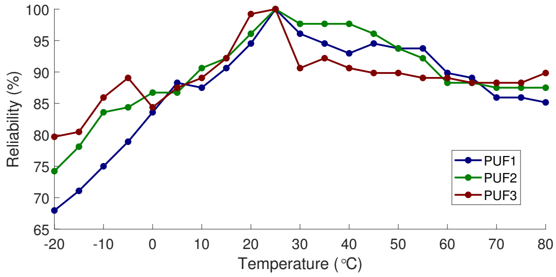


Fig. 7 Monocrystalline silicon reliability with respect to temperature

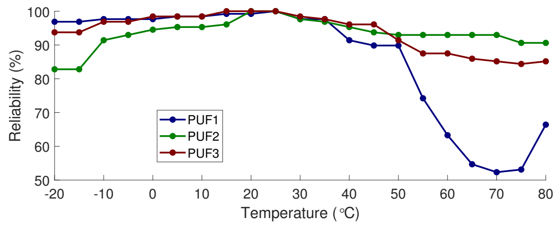


Fig. 8 Polycrystalline silicon reliability with respect to temperature

The polycrystalline silicon PUFs displayed the highest average reliability at 91.20% while the amorphous silicon PUFs displayed the lowest average reliability at 84.41%. The monocrystalline PUF displayed the most consistency as it was the only type to have the reliability values of each copy fall within 2.5 percentage points of each other.

Table 3 Average Reliability with Respect to Temperature

	PUF1	PUF2	PUF3	Overall
Amorphous	96.39 %	75.41 %	81.44 %	84.41 %
Monocrystalline	87.57 %	89.84 %	89.21 %	88.87 %
Polycrystalline	86.31 %	93.38 %	93.90 %	91.20 %

5.2.2 Uniformity Testing

Figure 9 shows the uniformity values of the amorphous silicon PUFs and Table 4 shows the average uniformity values for each copy of the PUF across the measured temperature range. The three amorphous silicon PUFs produced a combined average uniformity of 49.34% across the tested temperature range.

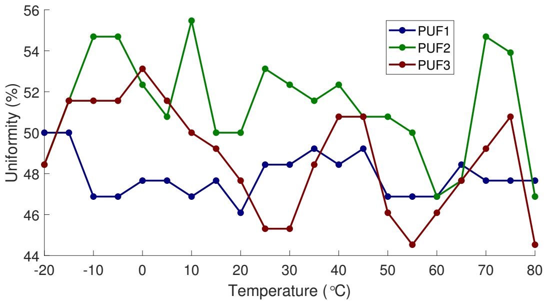


Fig. 9 Amorphous silicon uniformity with respect to temperature

Figure 10 shows the uniformity values for each of the monocrystalline silicon PUFs and Table 4 contains the average uniformity for each copy of the PUF. Overall, the monocrystalline silicon PUFs had a combined average uniformity of 49.47%.

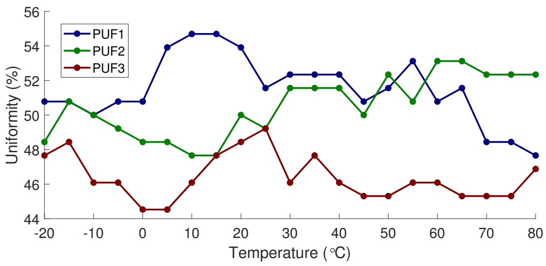


Fig. 10 Monocrystalline silicon uniformity with respect to temperature

Figure 11 shows the uniformity values for each of the polycrystalline silicon PUFs and Table 4 contains the average uniformity for each copy of the PUF. Overall, the polycrystalline silicon PUFs had a combined average uniformity of 51.26%

Despite changes in temperature, the uniformity values for each response generated by the different PUFs remained near the ideal value of 50%. The monocrystalline silicon PUFs had the average uniformity closest to the ideal value at 49.47%. Even though the polycrystalline silicon PUFs had the worst overall average uniformity, their overall average value of 51.26% was still close to the ideal value.

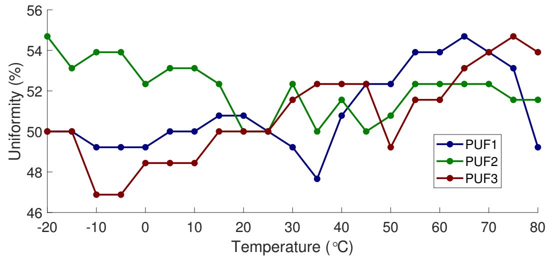


Fig. 11 Polycrystalline silicon uniformity with respect to temperature

Table 4 Average Uniformity with Respect to Temperature

	PUF1	PUF2	PUF3	Overall
Amorphous	47.88 %	51.38 %	48.77 %	49.34 %
Monocrystalline	51.49 %	50.52 %	46.39 %	49.47 %
Polycrystalline	50.97 %	52.08 %	50.74 %	51.26 %

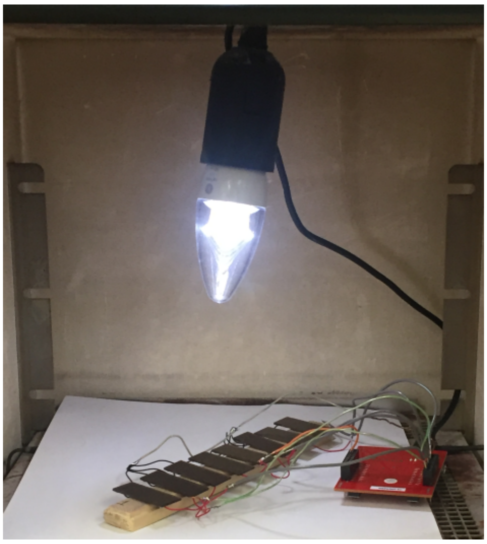


Fig. 12 Light intensity testing chamber

5.3 Testing with Respect to Light Intensity

Unlike in standard CMOS ICs, light intensity plays a major role in controlling the electrical properties of solar cells. It is therefore very important to analyze the performance of our proposed PUFs against variations in light intensity. Testing was performed by using a variable transformer to vary the intensity of a LED bulb from $40 Watts/m^2$ to $90 Watts/m^2$. Readings were taken in increments of $5 Watts/m^2$ and $40 Watts/m^2$ was used as the reference for reliability testing. Our tested range was directly influenced by the testing facilities available to us. The complete testing setup is shown in Figure 12.

5.3.1 Reliability Testing

Figure 13 shows the reliability values of the amorphous silicon PUFs and Table 5 shows the average reliability values for each copy of the PUF across the measured range of light intensities. The three amorphous silicon PUFs produced a combined average reliability of 97.75% across the tested range.

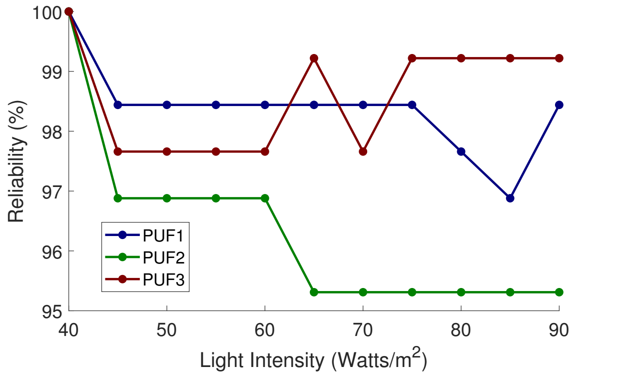


Fig. 13 Amorphous silicon reliability with respect to light intensity

Figure 14 shows the reliability values for each of the monocrystalline silicon PUFs and Table 5 contains the average reliability for each copy of the PUF. The first copy of the PUF (PUF1) demonstrated a sharper drop in reliability as light intensity increased when compared to the other instances of the PUF (PUF2 and PUF3). Overall, the monocrystalline silicon PUFs had a combined average reliability of 96.12%.

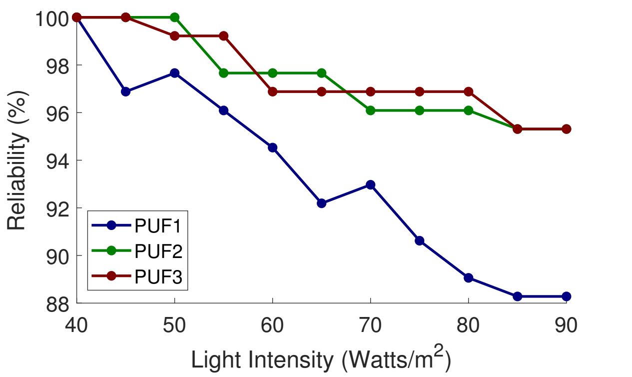


Fig. 14 Monocrystalline silicon reliability with respect to light Intensity

Figure 15 shows the reliability values for each of the polycrystalline silicon PUFs and Table 5 contains the average reliability for each copy of the PUF. The second copy of the PUF (PUF1) demonstrated a gradual decline in reliability as light intensity increased whereas the other instances of the PUF (PUF1 and PUF3) remained very consistent. Overall, the polycrystalline silicon PUFs had a combined average reliability of 95.45%

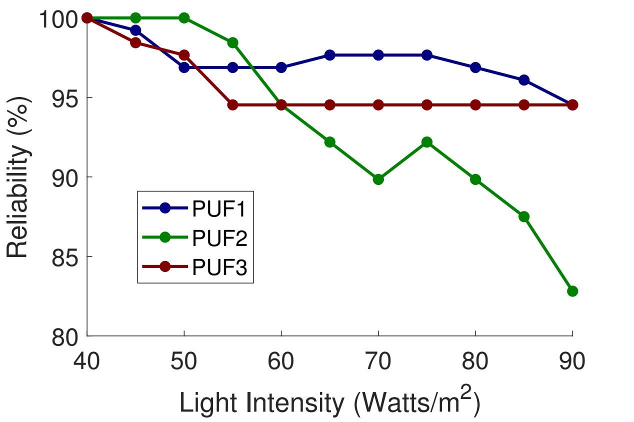


Fig. 15 Polycrystalline silicon reliability with respect to light Intensity

All of the PUFs tended to show resistance to changes in light intensity. The reliability tended to only gradually degrade as the light intensity increased with seven of the nine tested PUFs never dipping below 90%. The amorphous silicon has the highest overall average reliability at 97.75% while even the worst one (polycrystalline) was still above 95% at 95.45%.

Table 5 Average Reliability with Respect to Light Intensity

	PUF1	PUF2	PUF3	Overall
Amorphous	98.37 %	96.31 %	98.58 %	97.75 %
Monocrystalline	93.32 %	97.44 %	97.59 %	96.12 %
Polycrystalline	97.30 %	93.39 %	95.67 %	95.45 %

5.3.2 Uniformity Testing

Figure 16 shows the uniformity values of the amorphous silicon PUFs and Table 6 shows the average uniformity values for each copy of the PUF across the measured range of light intensities. The three amorphous silicon PUFs produced a combined average uniformity of 50.00% across the tested range. There was little variation in the uniformity values for each PUF as light intensity increased. However, the second copy of the PUF (PUF2) was noticeably higher than the other two copies (PUF1 and PUF3).

Figure 17 shows the uniformity values for each of the monocrystalline silicon PUFs and Table 6 contains

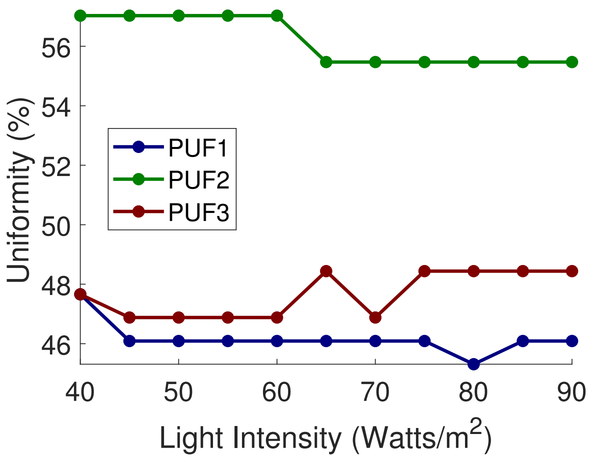


Fig. 16 Amorphous silicon uniformity with respect to light intensity

the average uniformity for each copy of the PUF. Overall, the monocrystalline silicon PUFs had a combined average uniformity of 52.81%.

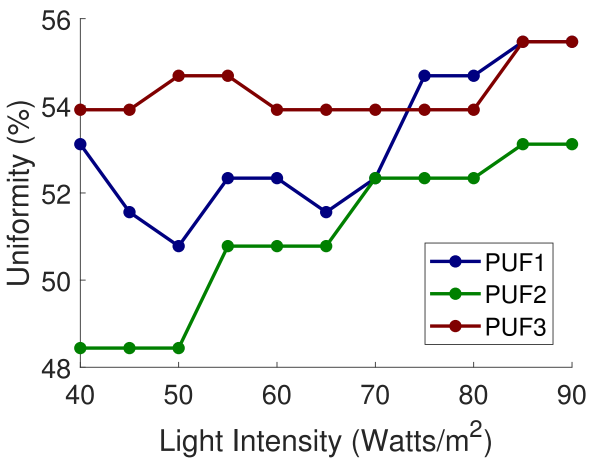


Fig. 17 Monocrystalline silicon uniformity with respect to light intensity

Figure 18 shows the uniformity values for each of the polycrystalline silicon PUFs and Table 6 contains the average uniformity for each copy of the PUF. Overall, the polycrystalline silicon PUFs had a combined average uniformity of 48.74%

Variations in light intensity did not appear to have any consistent effect on the uniformity of the responses generated by each type of PUF. The uniformity value for each copy of the different PUFs remained close to the ideal value of 50% and the average uniformity for the amorphous silicon PUFs was was the best exactly 50.00%. However, it is worth noting that this PUF also

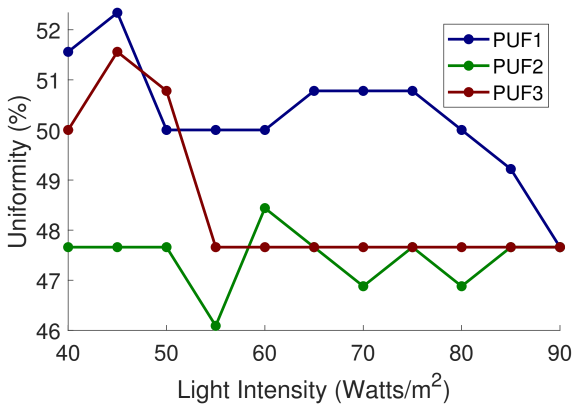


Fig. 18 Polycrystalline silicon uniformity with respect to light intensity

had the lowest recorded uniformity at 46.16% and the highest at 56.18%.

Table 6 Average Uniformity with Respect to Light Intensity

	PUF1	PUF2	PUF3	Overall
Amorphous	46.16 %	56.18 %	47.66 %	50.00 %
Monocrystalline	53.12 %	50.99 %	54.33 %	52.81 %
Polycrystalline	50.28 %	47.44 %	48.51 %	48.74 %

5.4 Uniqueness Testing

Uniqueness testing requires testing a relatively large number of PUF instances. Since creating that many physical PUF copies is not typically feasible, it is standard to perform Monte Carlo simulations in order to evaluate the uniqueness property of proposed PUFs. Unfortunately, the datasheets associated with our specific choices of solar cells only provide typical electrical parameter values. This makes it impossible for us to accurately generate the normal distribution of cells that would be required for a Monte Carlo simulation.

This closest approximation would be to use values for the the different solar cell materials that have been reported by other literature sources. Monocrystalline solar cells were previously reported to have a possible voltage range of $\pm 5\%$ [28]. The values reported in that work have been used by other works which have proposed methods for generating mathematical models of solar cell parameters [27]. Using this range we can generate a normal distribution of 8000 solar cells and randomly select 8 at a time to created 1000 simulated PUFs. The uniqueness calculated for the responses was 49.989% which is very close to the ideal value of 50%.

6 Discussion

In general, solar cells have been utilized as a power source for various IoT devices such as wireless sensors, RFIDs, etc. In this paper, we have utilized the intrinsic variations between solar cells to create a PUF. Doing so effectively allows the solar cells to be used as a method for adding security features to these devices.

When compared to existing silicon PUFs, our design has the distinction that it could theoretically be implemented by a device without adding additional hardware. The integration of a silicon PUF would require a specially designed circuit which would not already exist on the device. Our proposed design methodology and Silicon PUF designs are not necessarily direct competitors despite the fact that they are both PUFs. Our proposed approach was specifically designed for applications where it was impossible to implement a Silicon PUF (e.g. adding security without adding hardware).

In this work we evaluated three different types of solar cell materials by performing temperature testing for the range -20°C to 80°C and light intensity testing for the range 40 $Watts/m^2$ to 90$Watts/m^2$. Each test was conducted on three copies of each type of PUF. We also evaluated the uniqueness of monocrystalline silicon through Monte Carlo simulations on a population of 1000 simulated PUFs.

In our experiments, we created PUFs using Panasonic AM-1417CA amorphous silicon solar cells ($V_{oc} = 2.4V$), IXYS KXOB22-12X1F monocrystalline solar cells ($V_{oc} = 630mV$), and AOSHIKE micro solar panel polycrystalline silicon solar cells ($V_{out} = 2V$). We created three copies of each PUF per type of solar cell for a total of nine PUFs. This allowed us to begin creating performance benchmarks for some popular types of solar cells when they are used in the creation of PUFs. Each copy was created from randomly chosen solar cells of each type. This means there is not anything purposely different between the different copies of a PUF per each type of solar cell. Any variation in testing results among the three copies of a given material should be a manifestation of their random intrinsic variations. This means that in tests where one PUF has noticeably different performance than the other two copies, those differences are the result of random chance rather than an explicit difference between the PUF copies. An example of this can be seen in the testing of reliability with respect to temperature for amorphous silicon where PUF1 had noticably different performance than PUF2 and PUF3.

On average, the polycrystalline silicon based PUFs had the best reliability with respect to temperature at 91.20% while the amorphous silicon based PUFs had the worst average reliability at 84.41%. Their standings are actually inverted with respect to Light Intensity as polycrystalline silicon had the worst average reliability at 95.45% and amorphous silicon had the best value at 97.74%. In addition, the uniformity values of the responses generated from these PUFs were also recorded and the average values for each type of solar cell were sufficiently close to the ideal value of 50%.

Based on the results of our testing, it can be inferred that polycrystalline solar cells are the ideal choice for PUFs that will be subjected to large variations in temperature. Our results also indicate that amorphous silicon solar cells are best suited for PUF applications where the major environmental concern is variation in light intensity. However, it is also worth considering the fact that the reliabilities with respect to light intensity were consistently higher than the reliabilities with respect to temperature. This would seem to imply that the PUFs have a higher resistance to light intensity variations than they do to temperature variations for at least over the range that we tested. In an application scenario where variations in light intensity are the primary concern, special considerations must be made to ensure that any variations in temperature will be kept to an absolute minimum. Otherwise, seemingly minor changes in temperature could cause amorphous silicon to go from being the best option of our tested types of solar cells to the worst option.

Although we were not able to perform uniqueness testing on the specific cells used in our prototypes, we were at least able to evaluate the uniqueness of monocrystalline silicon solar cells. Through Monte Carlo simulation of 1000 simulated PUFs, it was determined that the uniqueness was 49.989%. While we can't draw any firm conclusions about PUFs constructed using amorphous silicon or polycrystalline silicon solar cells, the monocrystalline results are at the least not a discouraging sign for the uniqueness prospects of the other materials.

Based on the results of our testing we have noticed a curious trend related to the reliability of the cells with respect to temperature. The temperature coefficient of a solar cell is a measure how well the performs with respect to changes in temperature. The closer the coefficient is to 0% then the less the cell's output will drop as the temperature increases. Therefore, a lower temperature coefficient indicates better performance with respect to temperature. Among the materials we tested, researchers have shown amorphous silicon to perform the best as temperatures increase. That is followed by monocrystalline silicon solar cells with the next best performance, and polycrystalline had the worst performance [7] [9]. Based on these characteristics one would expect to see the PUFs constructed from these materials to exhibit the same relative performance when it comes to their reliability with respect to temperature. However, our testing has revealed the pollycrystalline PUF to have the best reliability with respect to temperature followed by monocrystalline and then amorphous. This is the exact inverse of their normal performance with respect to temperature. Determining what the reason is for the inverse correlation between temperature coefficients and PUF reliability could be further investigated as a future work.

7 Conclusion

In this paper, we have proposed a design methodology to create PUFs from solar cells. This PUF uses the open-circuit voltages from the individual solar cells as the source of entropy in generating responses. Furthermore, we created copies of the PUF based around three different types of solar cells: amorphous silicon, monocrystalline silicon, and polycrystalline silicon. We evaluated the reliability and uniformity of our proposed design over a temperature range of -20°C to 80°C and a light intensity range of $40 Watts/m^2$ to $90 Watts/m^2$. From our testing we determined that the polycrystalline silicon PUFs had the highest average reliability with respect to temperature at 91.20% and the amorphous silicon PUFs had the highest average reliability with respect to light intensity at 97.74%. Furthermore, our Monte Carlo simulations on monocrystalline silicon showed that a PUF based on monocrystalline solar cells could have a uniqueness value of 49.989%.

The exploratory nature of this work presents multiple avenues for future work. There are other solar cell materials besides the three we evaluated which could similarly be suitable for the creation of PUFs. Our testing was performed with limited sample sizes. However, the results are encouraging and thus warrant further testing over greatly expanded sample populations. One potential future area of work would be performing more thorough investigations on a larger population. Large scale testing could be of interest for commercialization purposes where it would be useful to generate results that can be considered as accurate as possible for the entire population. Large scale testing would also allow for uniqueness testing to be performed on actual physical devices rather than simulated copies.

A further goal would be to improve the design to allow the solar cells to act as both a source of power and a source of entropy for the PUF. Standard solar cell usage only provides the former while our proposed design only allows for the latter. Combining the two should be feasible, but the actual circuit must still be designed. This would allow the PUF to effectively serve as a source of both power and security and ease its integration into IoT devices. As part of this integration, it would be worth exploring how best to integrate this behavior so that its operation does not run into conflict with the real time nature or other operating constraints of the devices.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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