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PHYSICAL UNCLONABLE FUNCTION (PUF) SECURITY KEY GENERATION

Abstract

Systems and methods of generating a security key for an integrated circuit device include generating a plurality of key bits with a physically unclonable function (PUF) generator. Unstable bits of the plurality of key bits are identified, and a security key is generated based on the plurality of key bits, wherein the security key excludes the identified unstable bits.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION [0001] This application is a continuation of U.S. patent application Ser. No. 18/517,801, filed on Nov. 22, 2023, which is a continuation of U.S. patent application Ser. No. 17/215,765, filed on Mar. 29, 2021, which is a continuation of U.S. patent application Ser. No. 16/171,747, filed on Oct. 26, 2018, now U.S. Pat. No. 10,965,475, which claims the benefit of U.S. Provisional Patent Application No. 62/591,957, filed on Nov. 29, 2017, the disclosures of which are incorporated by reference herein.

BACKGROUND

[0002] As reliance on computer systems and the internet increases in many areas such as personal communications, shopping, banking, commerce, etc., the need for improved cyber security also increases. Many security measures may be employed, including cryptography. A physical unclonable function (PUF) is a physical object embodied in a physical structure that can be used to produce an output. The output is easy to evaluate but the output is very hard or nearly impossible to predict. A PUF can be used as a unique identification or key in secure computing and communication.

[0003] An individual PUF device must be easy to make but practically impossible to duplicate, even given the exact manufacturing process that produced it. In this respect it is the hardware analog of a one-way function. PUFs are typically implemented in integrated circuits and are typically used in applications with high security requirements.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0005] FIG. 1 is a block diagram illustrating aspects of an example system for generating a physically unclonable function (PUF) security key in accordance with some embodiments.

[0006] FIG. 2 is a block diagram illustrating aspects of an example authentication circuit of FIG. 1 in accordance with some embodiments.

[0007] FIG. 3 is a block diagram illustrating aspects of an example static random access memory (SRAM) of the PUF generator of FIG. 2 in accordance with some embodiments.

[0008] FIG. 4 is a circuit diagram illustrating further aspects of the example SRAM PUF generator of FIG. 3.

[0009] FIG. 5 is a process flow diagram illustrating aspects of a method for generating a PUF security key in accordance with some embodiments.

[0010] FIG. 6 is a process flow diagram illustrating further aspects of an example method for generating a PUF security key in accordance with some embodiments.

[0011] FIG. 7 is a block diagram illustrating further aspects of an example method for generating a PUF security key in accordance with some embodiments.

[0012] FIG. 8 is a process flow diagram illustrating further aspects of an example challenge and response process in accordance with some embodiments.

DETAILED DESCRIPTION

[0013] The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

[0014] Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

[0015] As noted above, a physical unclonable function (PUF) is a physical object embodied in a physical structure that can be used to produce an output that is easy to evaluate but nearly impossible to predict. Integrated circuit (IC) devices generally include electronic circuits formed on a semiconductor substrate, or “chip,” formed of a semiconductor material such as silicon. Components of IC devices are formed on the substrate by a photolithography process rather than being constructed one item at a time. The electronic devices formed on the substrate are interconnected by conductors, or wires, also formed on the substrate by photolithographic processes. Although manufactured in high volume, each IC device is unique due to physical randomness, even with the same manufacturing processes materials. This inherent variation can be extracted and used as its unique identification, as DNA to human beings. In accordance with embodiments disclosed herein, such variation is used to create a unique IC device signature used as a PUF, since it is unique, inherent to the particular device, unclonable (cannot be mimicked or duplicated), repeatable, etc.

[0016] FIG. 1 is a block diagram illustrating an example of an integrated circuit device **10** in accordance with aspects of the present disclosure. The integrated circuit device **10** includes a substrate **12** that forms an electronic device **20**, which could be any of various types of devices implemented by an integrated circuit, such as a processing or memory device. An authentication circuit **100** is configured to receive a challenge via an input/output port **102**. In response to the challenge, the authentication circuit is configured to provide a response in the form of a security key, which is output by a PUF generation circuit. As noted above, a PUF is constructed based on the occurrence of different physical process variations during the manufacturing of an IC. These static physical variations allow an IC to have a unique fingerprint (or multiple unique fingerprints) particular to the IC. When a particular challenge received via the input/output port **102**, a corresponding unique response is generated. An IC that is capable of generating multiple fingerprints is a strong PUF, since multiple challenge and response pairs are available.

[0017] With some PUF generation techniques, some potential security key bits may vary from one PUF generation to another. In this disclosure, such key bits are referred to as unstable bits. In general, these unstable bits are not suitable to be used for key generation because messages encrypted with a key having unstable bits may not be deciphered reliably. Collecting and

identifying the location of the useful bits becomes very important to generate a unique and reliable key per IC device. In some examples disclosed herein, rather than keeping a record of stable key bits for use in generating security keys, records of unstable bits are maintained. In the embodiment shown in FIG. 1, the unstable bits are stored in the memory **110**. Generating the security key includes accessing the unstable bits memory **110**, and then outputting a response key that excludes the identified unstable bits.

[0018] FIG. 2 illustrates further aspects of an example of the authentication circuit **100**. A PUF generator **120** is configured to generate a security key that includes a predefined number of key bits. As noted above, the security key is provided in response to a received challenge, and is unique to the particular IC device **10** due to inherent variations resulting from the manufacturing process for the device. In some examples, the PUF generator **120** includes a memory array, such as an SRAM memory array, where the memory cells of the array generate key bits of the security key. The size of the SRAM array may be determined based on the size of the required security key(s).

[0019] Processing memory **122** is provided for PUF data processing. In the illustrated example, the processing memory **122** is an SRAM. A request for a security key is received in the form of a challenge. A challenge-response processor **124** handles such a request, or challenge, to ensure correctness of the challenge before presenting the challenge to the PUF generator **120**. Based on a valid response, a security key is generated by the PUF generator **120**. In some examples, the challenge-response processor **124** processes the response by removing bits that are not useful and ensures the correct size of the security key is generated.

[0020] In the particular embodiment shown in FIG. 2, the unstable bits memory **110** comprises a nonvolatile memory provided on the device **10** itself. In other examples, the unstable bits memory is located external to the device **10**. In FIG. 2, the unstable bits memory **110** is an eFUSE nonvolatile memory, which marks the address(s) of identified unstable bits in the PUF. As will be discussed further below, initially the unstable bits memory **110** contains no information. During a commissioning process, the unstable bits memory **110** is updated with unstable bit addresses at the end of each of a plurality of test steps. At the end of all the test steps, the unstable bits memory **110** will contain information about all unstable bits. This information is used by the challenge-response processor to generate the security key in response to a received challenge. The illustrated example further includes an unstable bits memory controller **130**. In examples where the unstable bits memory **110** is implemented via an eFUSE, the memory controller **130** interfaces with the unstable bits memory **110** for read and write modes.

[0021] The illustrated authentication circuit **100** further includes an authentication interface **140**, which is a state machine that provides an interface external to the device **10**. For example, the authentication interface **140** initiates access to the PUF generator and keeps track of all transactions related to the PUF access and data collection.

[0022] A PUF generator obtains the inherent differences among manufactured devices to generate the PUF signature. For example, there are delay chain based PUFs, wherein the PUF translates variations (difference) into delay variances. They employ a set of delay chains made out of logic gates. Due to static variations of components, each chain will have different delay. By sampling the delay, a signature can be produced.

[0023] Another approach is a memory-based PUF, wherein variations of devices in a bi-stable element are translated to generate either a "1" or "0". Such a memory-based PUF includes a memory cell array that may be implemented as any of a variety of memory cell arrays such as SRAM, DRAM, MRAM, RRAM, ROM, etc. A particular type of memory-based PUF is an SRAM PUF. These PUFs utilize small memory cell variations to produce signatures. For example, one type of SRAM PUF gets its signatures from the start up states of cells.

[0024] In some embodiments, the PUF generator includes a memory array upon which the PUF is based. For example, such an SRAM-based PUF uses the memory initial data content (power up condition) to generate the security keys. Bits of the generated key that do not change state from one

power up cycle to the next are referred to as stable bits. However, attempting to identify and record each stable bit to be used for key generation would require a significant amount of time, and recording the stable bits could possibly expose the key generation to side attacks. In addition, it would require a significant number of additional bits to correct errors due to environmental effects, noise and aging that might affect the stable bits of the memory.

[0025] In accordance with examples disclosed herein, unstable bits are identified using information available at the die manufacturing stage. Unstable bit identification is accumulated throughout various die test stages and conditions. The unstable bit information is used to generate a security key or multiple keys. The identified unstable bits may be stored in the unstable bit memory **110**, such as a nonvolatile memory provided on chip, or the unstable bits may be stored off chip as part of a security server database.

[0026] As noted above, some examples implement the PUF generator via an SRAM memory. For example, a PUF signature may be generated by using power-on states of an SRAM device. Even though an SRAM device includes symmetric cells (bits), manufacturing variability may still cause each bit of the SRAM device to tend to be at a high state (i.e., a logical “1”) or at a low state (i.e., a logical “0”) while the SRAM device is powered on. Such initial power-on states of the bits are randomly distributed across the whole SRAM device, which gives rises to a variability that can be defined by a PUF to produce a unique key of the SRAM device.

[0027] In other embodiments where an SRAM is used as a PUF generator, each bit of a security key is generated by comparing accessing speeds (e.g., reading speeds) of two memory cells of the memory device. In such examples, since the PUF signature is based on the comparison of reading speeds, no iteration to power up and down the memory device is required.

[0028] FIG. 3 illustrates portions of an exemplary SRAM circuit **200** used to implement the PUF generator **120** in some embodiments. The SRAM implementing the PUF generator **120** includes a plurality of cells that generate bits of the security key. The SRAM **200** includes a memory cell array **202**, a PUF generation circuit **204**, a row decoder **208**, and an I/O circuit **212**.

[0029] The SRAM memory cell array **202** includes a plurality of SRAM memory cells (e.g., **221**, **229**, **231**, **239**, **241**, **249**, **251**, **259**, **261**, **269**, **291**, **299**) arranged in a column-row configuration. One or more cells may be disposed between the cells **221** and **229**, **231** and **239**, and so on. Each column of memory cells has a respective pair of bit lines (BL) and bit lines bar (BLB) that are coupled to the cells in that column, and each row has a respective word line (WL) that is coupled to multiple cells that respectively belong to multiple columns. For example, as illustrated in the SRAM cell array **202** of FIG. 3, the leftmost column has BL **222** and BLB **224**, the next column has BL **232** and BLB **234**, and so on. The cells of each column are coupled to the respective column's BL and BLB. For example, in FIG. 3, the cells **221** and **229**, and any cells coupled therebetween are each coupled to the BL **222** and BLB **224**. Further, the cells **221**, **231**, **241**, **251**, **261**, and up to **291** arranged in the top row are each coupled to the WL **220**; and the cells **229**, **239**, **249**, **259**, **269**, and up to **299** arranged in the bottom row are each coupled to the WL **240**.

[0030] The I/O circuit **212** is coupled to the BL and BLB of each column. For example, the I/O circuit **212** includes a plurality of sense amplifiers that are coupled to the BL **222** and BLB **224** of each respective column of the memory array **202**. Such sense amplifiers of the I/O circuit **212** are each configured to compare a voltage difference between the coupled BL and BLB to which a cell is coupled so as to read bit data stored in that cell.

[0031] The PUF generation circuit **204** is coupled to each cell of the memory array, whereby the cells of the memory array comprise key bits of the security key **205** that is output in response to the receive challenge. In the illustrated example, each of the key bits of the security key **205** is generated by comparing accessing speeds of two memory cells of the memory device **200**.

[0032] FIG. 4 illustrates details of two adjacent memory cells **221** and **231** of the SRAM cell array **202**. The memory cells **221** and **231** are coupled to a sense amplifier **204-1** of the PUF generation circuit **204**. While the memory cells **221** and **231** are each implemented as a 6-transistor SRAM

(6T-SRAM) cell, the SRAM **200** is not limited to being implemented as a 6T-SRAM cell.

[0033] Referring still to FIG. **4**, cell **221** includes transistors **M1**, **M2**, **M3**, **M4**, **M5**, and **M6**; and cell **231** includes transistors **M11**, **M12**, **M13**, **M14**, **M15**, and **M16**. In some embodiments, the cells **221** and **231** are substantially similar to each other, that is, transistor **M1** is substantially similar to transistor **M11**; transistor **M2** is substantially similar to transistor **M12**; transistor **M3** is substantially similar to transistor **M13**; transistor **M4** is substantially similar to transistor **M14**; transistor **M5** is substantially similar to transistor **M15**; and transistor **M6** is substantially similar to transistor **M16**. Thus, for clarity, the following discussions of configurations and operations of the transistors of the cell will be directed to the cell **221** only.

[0034] As illustrated in FIG. **4**, the transistor **M2** and **M3** are formed as a first inverter and the transistors **M4** and **M5** are formed as a second inverter wherein the first and second inverters are coupled to each other. More specifically, the first and second inverters are each coupled between a first voltage reference **301** and second a voltage reference **303**. Generally, the first voltage reference **301** is a voltage level of a supply voltage V_{dd} applied on the cell **221**, and the second voltage reference **303** is ground. The first inverter is coupled to the transistor **M1**, and the second inverter is coupled to the transistor **M6**. In addition to being coupled to the inverters, the transistors **M1** and **M6** are both coupled to a WL **220** and each are coupled to bit line BL **222** and BLB **224**, respectively.

[0035] In general, when an SRAM cell stores a data bit, a first node of the SRAM cell is configured to be at a first logical state (1 or 0), and a second node of the SRAM cell is configured to be at a second logical state (0 or 1), wherein the first and second logical states are complementary with each other. In some embodiments, the first logical state at the first node is the data bit stored by the SRAM cell. For example, the illustrated embodiment of FIG. **4** includes nodes **305** and **307**. When the cell **221** stores a data bit (e.g., a logical 1), the node **305** is configured to be at the logical 1 state, and the node **307** is configured to be at the logical 0 state.

[0036] To generate the key **205**, in some embodiments, initially, a data bit (e.g., either a logical 1 or 0) is written to each of the cells in the SRAM array **202** to be read. Following the write operation(s), a row decoder of the SRAM **200** receives a row address to locate (determine) a WL at that row address and then the WL is asserted by a row decoder. In response to the WL being asserted (e.g., **220**), the access transistors (e.g., **M1**, **M6**, **M11**, **M16**), disposed along and coupled to the WL, are activated (i.e., turned on). In some examples, all or part of the BLs and BLBs (e.g., **222**, **224**, **232**, and **234**) of the SRAM **200** are either pre-charged to V_{dd} or pre-discharged to ground. Then the data bit stored (being written) in each cell (e.g., **221** . . . etc.) of the row (i.e., along the asserted WL) is read through the cell's respectively coupled BL (e.g., **222**) and BLB (e.g., **224**).

[0037] While the data bits are being read, the sense amplifier **204-1** coupled to the BLs **221-1**, **232-1** compares reading speeds (i.e., either the charging rates or the discharging rates) of the two adjacent cells. In response to the comparison, the sense amplifier **204-1** generates a bit (e.g., **205-1**) of the security key **205**. As such, for a particular row (WL) being asserted, a first plurality of bits (e.g., **205-1**, **205-2**, **205-3** . . . **205-4**) of the security key **205** may be (simultaneously) generated by the sense amplifiers of the authentication circuit **204**. In some embodiments, each of the other rows (WLs) in the memory cell array is subsequently asserted. Accordingly, one or more pluralities of bits of the PUF signature may be generated by the sense amplifiers of the authentication circuit **204**.

[0038] FIG. **5** is a process flow diagram generally illustrating aspects of an example method **400** for generating a security key, such as the security key **205** discussed above. At block **410**, a plurality of key bits are generated. As noted previously, the key bits may be generated by a PUF generator implemented via an SRAM memory array such as the array **202**, for example. At block **412**, at least one unstable bit of the plurality of key bits generated in block **410** is identified. As used herein, unstable bits are security key bits that vary from one PUF generation to another. At

block **414**, a security key is generated, such as the security key **205**. The security key generated in block **414** excludes identified unstable bits.

[0039] In some implementations, the integrated circuit device chip **10** goes through a commissioning phase to identify and to register the chip PUF, which may include creating a challenge-response reference database that is saved in a suitable computer device. For example, the challenge-response reference database may be saved as part of a security database of a server that intends to authenticate the integrated circuit device **10**.

[0040] The database is generated from test data collected at a plurality of test stages. As noted above, saving unstable bits in an on-chip memory may reduce the amount of data eventually saved on an external server. FIG. **6** illustrates an example process **430** that may be used to generate one or more security keys. In general, PUF data are collected for a plurality of test conditions, such as varying temperatures, voltage levels, etc. Block **432** shows a first test condition A. For this test condition, the PUF is read from the PUF generator **120** (FIG. **2**) at block **434**, and copied to a first memory, such as the processing SRAM **122**.

[0041] The PUF is read multiple times to identify bits that vary from one PUF generation to another-the unstable bits. Thus, each occurrence of generated PUF is read at block **436** and compared to the earlier occurrence of the PUF data saved in the first memory. Thus, as shown at block **438**, for each read of the generated PUF at block **436**, a second memory (i.e. the unstable bits memory **110**) is updated with data indicating unstable bits (bits that change from one read to another). This continues until all PUF reads are completed as determined in the decision block **440**. In some examples, the PUF is read at least five times.

[0042] FIG. **7** provides an example conceptually illustrating the process of updating the unstable bits memory **110**. Various bits (bit 0, bit 1 to bit n) of the generated PUF are illustrated. Data obtained from the first read **436-1** results in 1, 1, 0 for bit 0, bit 1, and bit n, respectively. Data obtained from the second read **436-2** results in 1, 0, 0 for bits bit 0, bit 1, and bit n, respectively. Since the data read for bit 1 changed from the first read **436-1** to the second read **436-2**, the XOR function of block **438** identifies bit 1 as an unstable bit, which is saved in the unstable bits memory **110**.

[0043] Returning to FIG. **6**, when all of the PUF reads have been completed as indicated in the decision block **440**, the unstable bits memory **110** will contain all of the identified unstable bits. As determined in decision block **442**, if additional test conditions remain, the process is repeated to identify further unstable bits. Once the process is complete, the unstable bits may be saved to an external server database.

[0044] In some examples, the challenge (C) is provided as a memory address. Generating the server database thus requires reading the security key **205** from the address contained in the challenge, and removing the unstable bits as identified by the unstable bits memory **110** to generate the security key response corresponding to the challenge address. By eliminating the unstable bits, the security key is comprised of only stable bits. In some embodiments, error correction code (ECC) is further calculated for the response. The ECC helps ensure correct security key generation under extreme environments, for example. Such conditions could include those that exceed the conditions experienced during the commissioning tests. The challenge-response database, for example, thus includes the security key response bits (R) stored along with the ECC bits (ECC) as pair: C (R,ECC).

[0045] FIG. **8** illustrates an example of a challenge-response process **450**. The processes shown in FIG. **8** are discussed in conjunction with FIGS. **1** and **2**. At block **452**, a challenge is received, such as from a server desiring to authenticate the device **10**. The challenge is composed of a challenge address (Address[x]) and Error Correction Code bits (ECC[y]). A Strong PUF supports multiple (x, y) pairs. Upon receiving the challenge, the challenge-response processor **124** of the authentication circuit **100** reads the bits corresponding to the challenge address[x] generated by the PUF generator **120** in block **454**. The read PUF data is then processed to remove (filter) the unstable bits at block

456. This includes, for example, accessing the unstable bits memory **110** to identify the unstable bits of the generated PUF data. The challenge-response processor **124** stores the key bits in a key register as shown at block **458**, and the process is repeated until all the key bits have been read as determined in block **460**. In block **462** the ECC part of the challenge ECC[y] is then used to correct any error in the filtered data to achieve the final security key. At block **464** the key is presented as the response from the challenge response process **450**.

[0046] Thus, disclosed embodiments include a method of generating a security key for an integrated circuit device that includes generating plurality of key bits, identifying one or more unstable bits of the plurality of key bits, and generating a security key based on the plurality of key bits, wherein the security key excludes the at least one unstable bit.

[0047] In accordance with further disclosed embodiments, an integrated circuit device includes a PUF generator configured to output a plurality of key bits. A memory stores unstable bits of the plurality of key bits, and a controller is configured to generate a security key in response to receiving a challenge, wherein generating the security key includes accessing the memory and excluding the unstable bits from the security key.

[0048] In accordance with still further disclosed embodiments, a system for generating an integrated circuit device security key includes a first memory storing a first occurrence of a first key bit, and a PUF generator configured to output a plurality of key bits, including a second occurrence of the first key bit. A processor is configured to compare the first and second occurrences of the first key bit to identify an unstable key bit.

[0049] The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1-20. (canceled)

21. A device, comprising: a first memory cell and a second memory cell; a physically unclonable function (PUF) generator configured to compare an access speed of the first memory cell to an access speed of the second memory cell, generate a plurality of key bits based on the comparison, identify at least one unstable bit of the plurality of key bits, and store the at least one unstable bit in a memory; and a controller configured to generate a security key in response to receiving a challenge, wherein generating the security key includes accessing the memory and excluding the at least one unstable bit from the security key.

22. The device of claim 21, wherein the PUF generator is configured to compare the access speed of the first memory cell to the access speed of the second memory cell by comparing a charging rate or a discharging rate of each of the first memory cell and the second memory cell.

23. The device of claim 21, wherein the PUF generator is configured to compare the access speed of the first memory cell to the access speed of the second memory cell by writing a predetermined data bit to each of the first memory cell and the second memory cell.

24. The device of claim 21, wherein the memory is an eFUSE nonvolatile memory.

25. The device of claim 21, wherein the PUF generator comprises the first memory cell and the second memory cell.

26. The device of claim 21, wherein the security key comprises an error correction code.

27. The device of claim 26, wherein the challenge includes a security key address and an error

correction code bit.

28. A method, comprising: comparing an access speed of a first memory cell to an access speed of a second memory cell; generating a plurality of key bits based on the comparison; identifying at least one unstable bit of the plurality of key bits; receiving a challenge; and generating a security key in response to receiving the challenge, wherein generating the security key includes excluding the at least one unstable bit from the security key.

29. The method of claim 28, further comprising storing the at least one unstable bit in a memory, wherein generating the security key includes accessing the memory.

30. The method of claim 28, wherein comparing the access speed of the first memory cell to the access speed of the second memory cell comprises writing a predetermined data bit to each of the first memory cell and the second memory cell.

31. The method of claim 28, wherein comparing the access speed of the first memory cell to the access speed of the second memory cell comprises comparing a charging rate or a discharging rate of each of the first memory cell and the second memory cell.

32. The method of claim 31, wherein identifying the at least one unstable bit of the plurality of key bits comprises: generating a plurality of security keys under a plurality of test conditions; and comparing key bits of the plurality of security keys.

33. The method of claim 28, wherein the security key comprises an error correction code.

34. The method of claim 33, wherein the challenge includes a security key address and an error correction code bit.

35. A device, comprising: a first memory cell and a second memory cell; a memory configured to store unstable bits; a physically unclonable function (PUF) generator configured to: compare an access speed of the first memory cell to an access speed of the second memory cell; generate a plurality of key bits based on the comparison; identify at least one unstable bit of the plurality of key bits; store the at least one unstable bit in the memory; and generate a security key in response to receiving a challenge, wherein generating the security key includes accessing the memory and excluding the at least one unstable bit from the security key.

36. The device of claim 35, wherein the PUF generator is configured to compare the access speed of the first memory cell to the access speed of the second memory cell by comparing a charging rate or a discharging rate of each of the first memory cell and the second memory cell.

37. The device of claim 35, wherein the PUF generator is configured to compare the access speed of the first memory cell to the access speed of the second memory cell by writing a predetermined data bit to each of the first memory cell and the second memory cell.

38. The device of claim 35, wherein the PUF generator comprises the first memory cell and the second memory cell.

39. The device of claim 35, wherein the memory is an eFUSE nonvolatile memory.

40. The device of claim 35, wherein the security key comprises an error correction code.
