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METHOD FOR FABRICATING PHYSICALLY UNCLONABLE FUNCTION DEVICE

Abstract

A method for fabricating a physically unclonable function (PUF) device includes the steps of first defining a PUF cell region on a substrate and then performing a process to form a defect on the PUF cell region. Preferably, the formation of the defect could be accomplished by forming a shallow trench isolation (STI) on the substrate, forming a gate material layer on the substrate and the STI, patterning the gate material layer to form a first gate material layer and a second gate material layer, and then forming an epitaxial layer between and connecting the first gate material layer and the second gate material layer.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation application of U.S. application Ser. No. 17/687,692, filed on Mar. 7, 2022. The content of the application is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The invention relates to a method for fabricating a physically unclonable function (PUF) device.

2. Description of the Prior Art

[0003] Even though integrated circuits are usually fabricated by similar processes with same materials, each of the integrated circuits could still have a unique feature or variation specific to itself. In recent years, researchers have come up with physical unclonable function (PUF) devices that utilizes specific variations in integrated circuits as a unique feature similar to human DNA. Due to its nature of randomness, the output of PUF devices are very difficult to predict thereby increasing its level of security.

SUMMARY OF THE INVENTION

[0004] According to an embodiment of the present invention, a method for fabricating a physically unclonable function (PUF) device includes the steps of first defining a PUF cell region on a substrate and then performing a process to form a defect on the PUF cell region. Preferably, the formation of the defect could be accomplished by forming a shallow trench isolation (STI) on the substrate, forming a gate material layer on the substrate and the STI, patterning the gate material layer to form a first gate material layer and a second gate material layer, and then forming an epitaxial layer between and connecting the first gate material layer and the second gate material layer.

[0005] These and other objectives of the present invention will no doubt become obvious to those of ordinary skill in the art after reading the following detailed description of the preferred embodiment that is illustrated in the various figures and drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 illustrates a perspective view of a PUF device according to an embodiment of the present invention.

[0007] FIGS. 2-7 illustrate a method for fabricating a cell region with defects of a PUF device according to an embodiment of the present invention.

[0008] FIG. 8 illustrates a method for fabricating a PUF device according to an embodiment of the

present invention.

[0009] FIG. 9 illustrates a method for fabricating a PUF device according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0010] Referring to FIG. 1, FIG. 1 illustrates a perspective view of a PUF device according to an embodiment of the present invention. As shown in FIG. 1, the PUF device preferably includes a PUF array **100**, which further includes a plurality of cell regions **102** carrying normal function and a plurality of cell regions **104** with defects. Referring to FIGS. 2-7, FIGS. 2-7 illustrate a method for fabricating a cell region **104** with defects of a PUF device according to an embodiment of the present invention. As shown in FIG. 2, a semiconductor substrate **12** made of semiconductor material including but not limited to for example silicon, germanium, silicon-germanium compounds, silicon carbide, or gallium arsenide is provided. Next, a shallow trench isolation (STI) **14** is formed in the substrate **12** to define a plurality of transistor regions having different conductive types. In this embodiment, the STI **14** is preferably made of silicon oxide, but not limited thereto. Next, an oxide growth process or more specifically a rapid thermal oxidation (RTO) process or an in-situ steam generation (ISSG) process is conducted to form a gate dielectric (not shown) made of silicon oxide on the substrate **12** and covering the surface of the substrate **12** and STI **14**.

[0011] Next, a gate structure is formed on the substrate **12**. In this embodiment, the formation of the gate structure could be accomplished by a gate first process, a high-k first approach from gate last process, or a high-k last approach from gate last process. Since this embodiment pertains to a gate first approach, a gate material layer **16** preferably made of polysilicon and a hard mask **18** made of silicon nitride (SiN) or silicon oxide could be formed sequentially on the gate dielectric layer or substrate. It should be noted that since the STI **14** is protruding above the surface of the substrate **12**, the top surface of the gate material layer **16** and hard mask **18** disposed on top of the STI **14** is also slightly higher than the top surface of gate material layer **16** and hard mask **18** disposed adjacent to two sides of the STI **14**.

[0012] Next, as shown in FIG. 3, a patterned mask **20** such as a patterned resist is formed on the hard mask **18**, in which the patterned mask **20** includes an opening exposing the top surface of the hard mask **18**.

[0013] Next, as shown in FIG. 4, a pattern transfer process is conducted by using the patterned mask **20** as mask to remove part of the hard mask **18**, part of the gate material layer **16**, and even part of the gate dielectric layer through single or multiple etching processes for forming an opening **22** exposing the top surface of the STI **14**. After stripping the patterned mask **20**, gate structures **24**, **26** each made of a patterned gate material layer **16** and a patterned hard mask **18** are formed on the substrate **12** adjacent to two sides of the STI **14**, in which each patterned gate material layer **16** preferably becomes a gate electrode for each region.

[0014] Next, as shown in FIG. 5, at least a spacer **28** is formed on sidewalls of the gate structures **24**, **26**. In this embodiment, the spacer **28** could be a single spacer or a composite spacer, in which the spacer **28** could further include an offset spacer (not shown) and a main spacer (not shown). The offset spacer and the main spacer are preferably made of different materials while the offset spacer and main spacer could all be selected from the group consisting of SiO₂, SiN, SiON, and SiCN, but not limited thereto.

[0015] Referring to FIGS. 6-7, FIGS. 6-7 illustrate a method for fabricating the PUF device taken from different views following FIG. 5 according to an embodiment of the present invention. As shown in FIG. 6, a dry etching and/or wet etching process could be conducted by using the gate structures **24**, **26** and the spacer **28** as mask to remove part of the substrate **12** for forming recesses **42** adjacent to two sides of the gate structures **24**, **26**. Next, a selective epitaxial growth (SEG) process is conducted to form epitaxial layers **44** in the recesses **42** as shown in FIG. 6 and at the same time form an epitaxial layer **30** on sidewalls of the gate material layer **16** directly above the

STI **14** for connecting the two gate structures **24, 26** as shown in FIG. **7**. It should be noted that even though epitaxial layers **44** formed in the substrate **12** adjacent to two sides of the gate structure **24** is disclosed in FIG. **6**, it would also be desirable to apply the same process for forming epitaxial layers **44** in the substrate **12** adjacent to two sides of the gate structure **26**, which is also within the scope of the present invention.

[0016] Viewing from a more detailed perspective, when the etching process is conducted to remove part of the substrate **12** for forming the recesses **42** as shown in FIG. **6**, part of the top portion of the spacers **28** directly on top of the STI **14** shown in FIG. **7** is removed at the same time to expose the sidewalls of the gate material layer **16** or gate electrode made of polysilicon and/or sidewalls of the hard mask **18**. Since the sidewalls of the gate material layers **16** of the two gate structures **24, 26** are exposed before the SEG process is conducted, the epitaxial growth process conducted afterwards would not only form epitaxial layers **44** in the substrate **12** adjacent to two sides of the gate structures **24, 26** as shown in FIG. **6** but also form epitaxial layer **30** on the exposed gate material layer **16** sidewall surfaces directly on top of the STI **14** as shown in FIG. **7** as the epitaxial layer **30** would be formed outwards and connect the two gate material layers **16**. In other words, an epitaxial layer **30** shaping as a bridge would be formed directly on top of the STI **14** during the epitaxial growth process to connect and directly contacting the gate material layer **16** and hard mask **18** from the gate structure **24** on left side and the gate material layer **16** and hard mask **18** from the gate structure **26** on right side as the epitaxial layer **30** preferably not contacting the STI **14** underneath directly.

[0017] It should be noted that the epitaxial layer **30** is formed between two gate structures **24, 26** in this embodiment to establish a connection between two gate structures **24, 26** that are not supposed to be connected. This thereby forms a defect and this defect then becomes an unique feature or unclonable characteristic for the chip or PUF device shown in FIG. **1**.

[0018] In this embodiment, the epitaxial layers **30, 44** could be formed to include different materials depending on the type of transistor being fabricated. For instance, if the MOS transistor being fabricated were to be a PMOS transistor, the epitaxial layers **30, 44** could be made of material including but not limited to for example SiGe, SiGeB, or SiGeSn. If the MOS transistor being fabricated were to be a NMOS transistor, the epitaxial layers **30, 44** could be made of material including but not limited to for example SiC, SiCP, or SiP. Moreover, the SEG process could also be adjusted to form a single-layered epitaxial structure or multi-layered epitaxial structure, in which heteroatom such as germanium atom or carbon atom of the structure could be formed to have gradient while the surface of the epitaxial layers **30, 44** is preferred to have less or no germanium atom at all to facilitate the formation of silicide afterwards. Next, one or more ion implantation process could be conducted to form source/drain regions **46** in the substrate **12** adjacent to two sides of the gate structures **24, 26**.

[0019] According to an embodiment of the present invention, the source/drain regions **46** could be formed by implanting p-type dopants during formation of a SiGe epitaxial layer, a SiGeB epitaxial layer, or a SiGeSn epitaxial layer for PMOS transistor, or could be formed by implanting n-type dopants during formation of a SiC epitaxial layer, SiCP epitaxial layer, or SiP epitaxial layer for NMOS transistor. By doing so, it would be desirable to eliminate the need for conducting an extra ion implantation process for forming the source/drain regions **46**. Moreover, the dopants within the source/drain regions **46** could also be formed with a gradient, which is also within the scope of the present invention.

[0020] Next, a contact etch stop layer (CESL) made of silicon nitride could be selectively formed on the substrate **12** to cover the gate structures **24, 26**, and then an interlayer dielectric (ILD) layer **32** is formed on the CESL. It should be noted that since the epitaxial layer **30** formed directly on top of the STI **14** for connecting the two gate structures **24, 26** does not contact the STI **14** underneath thereby forming a void between the STI **14** and the epitaxial layer **30**, the ILD layer **32** formed on the substrate **12** and covering the gate structures **24, 26** at this stage would also fill the

void between the STI **14** and epitaxial layer **30** completely at the same time. Nevertheless, it should also be noted that even though the void between the STI **14** and epitaxial layer **30** is filled with ILD layer **32** in this embodiment, according to other embodiment of the present invention, it would also be desirable to only form the ILD layer **32** on the gate structures **24**, **26** without filling the void, which is also within the scope of the present invention. Next, follow-up process could be carried out by performing a replacement metal gate (RMG) process to transform the gate structures **24**, **26** into metal gates or directly forming contact plugs adjacent to two sides of the gate structures **24**, **26** for connecting the source/drain regions. This completes the process for fabricating a PUF device according to an embodiment of the present invention.

[0021] Referring to FIG. **8**, FIG. **8** illustrates a method for fabricating a PUF device according to an embodiment of the present invention. As shown in FIG. **8**, in contrast to the aforementioned embodiment of forming the gate material layer **16** made of polysilicon immediately after the STI **14** is formed, it would be desirable to first form a patterned mask **34** such as patterned resist on the substrate **12** for exposing the surface of the STI **14** before forming the gate material layer **16** and then conduct a deep etching process **36** or treatment by applying diluted hydrofluoric acid (dHF) on the STI **14** for forming a defect. This defect then becomes a unique feature or unclonable characteristic for the chip or PUF device shown in FIG. **1**. Next, follow-up process could be conducted as shown in FIGS. **2-7** to form gate structures **24**, **26** on the substrate **12** and details of which are not explained herein for the sake of brevity.

[0022] Referring to FIG. **9**, FIG. **9** illustrates a method for fabricating a PUF device according to an embodiment of the present invention. As shown in FIG. **9**, it would also be desirable to conduct a heavy dosage ion implantation process **38** through Boolean approach on the STI **14** (such as the STI **14** on the right side of FIG. **9**) before forming the gate material layer **16** without using any patterned mask. Preferably, the ion implantation process **38** could be achieved by implanting ions such as germanium (Ge) or arsenic (As) into the STI **14** so that defect such as cavities or recesses could be formed more easily on edge portion of the STI **14** in the later etching process and this defect then becomes a unique feature or unclonable characteristic for the chip or PUF device shown in FIG. **1**. Next, follow-up process could be conducted as shown in FIGS. **2-7** to form gate structures **24**, **26** on the substrate **12** and details of which are not explained herein for the sake of brevity.

[0023] Overall, the present invention preferably discloses an approach for fabricating PUF device by first defining one or more PUF cell regions on a substrate and then performing a process to form a defect on at least one PUF cell region. According to an embodiment of the present invention, it would be desirable to form an epitaxial layer **30** between two gate structures **24**, **26** and by connecting and conducting the two adjacent gate structures **24**, **26** a defect could be formed. Moreover, it would also be desirable to conduct an etching process by using a patterned mask to conduct an etching process on the STI **14** for forming a defect, or conduct a heavy ion implantation process **38** through Boolean approach to implant ions such as germanium (Ge) or arsenic (As) into the STI **14** so that defect such as cavities could be formed on the edge of the STI **14** in the later etching process. All of the above three approaches for forming defects could all be used as a unique feature or unclonable characteristic for the PUF device.

[0024] Those skilled in the art will readily observe that numerous modifications and alterations of the device and method may be made while retaining the teachings of the invention. Accordingly, the above disclosure should be construed as limited only by the metes and bounds of the appended claims

Claims

1. A method for fabricating a physically unclonable function (PUF) device, comprising: defining a PUF cell region on a substrate; and performing a process to form a defect on the PUF cell region,

wherein the process comprises: forming a first gate material layer and a second gate material layer on the substrate; and forming an epitaxial layer between and connecting the first gate material layer and the second gate material layer.

2. The method of claim 1, wherein the process comprises: forming a shallow trench isolation (STI) on the substrate; forming a gate material layer on the substrate and the STI; patterning the gate material layer to form the first gate material layer and the second gate material layer; and forming the epitaxial layer between and connecting the first gate material layer and the second gate material layer.

3. The method of claim 2, further comprising: forming a hard mask on the gate material layer; forming a patterned mask on the hard mask; removing the hard mask and the gate material layer to form the first gate material layer and the second gate material layer and an opening exposing the STI; forming a first spacer adjacent to the first gate material layer and a second spacer adjacent to the second gate material layer; removing part of the first spacer and part of the second spacer; and forming the epitaxial layer.

4. The method of claim 3, further comprising forming the first spacer and the second spacer on the STI.

5. The method of claim 3, wherein the first gate material layer comprises polysilicon.

6. The method of claim 3, further comprising forming an interlayer dielectric (ILD) layer between the epitaxial layer and the STI.

7. The method of claim 3, further comprising forming a void between the epitaxial layer and the STI.
