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United States Patent	12389668
Kind Code	B2
Date of Patent	August 12, 2025
Inventor(s)	Lin; Meng-Han et al.

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### Polysilicon resistor structures

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#### Abstract

The present disclosure describes a method for forming polysilicon resistors with high-k dielectrics and polysilicon gate electrodes. The method includes depositing a resistor stack on a substrate having spaced apart first and second isolation regions. Further the method includes patterning the resistor stack to form a polysilicon resistor structure on the first isolation region and a gate structure between the first and second isolation regions, and doping the polysilicon resistor structure to form a doped layer in the polysilicon layer of the polysilicon resistor structure and source-drain regions in the substrate adjacent to the gate structure. Also, the method includes replacing the polysilicon layer in the gate structure with a metal gate electrode to form a transistor structure.

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**Appl. No.:** 18/516311

**Filed:** November 21, 2023

#### Prior Publication Data

<b>Document Identifier</b>	<b>Publication Date</b>
US 20240088139 A1	Mar. 14, 2024

#### Related U.S. Application Data

continuation parent-doc US 17870415 20220721 US 11869888 child-doc US 18516311  
division parent-doc US 16549077 20190823 US 11456293 20220927 child-doc US 17870415

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## Publication Classification

**Int. Cl.:** H01L27/06 (20060101); H01L21/8234 (20060101); H10D84/01 (20250101);  
H10D84/03 (20250101); H10D84/80 (20250101)

**U.S. Cl.:**

**CPC** H10D84/811 (20250101); H10D84/013 (20250101); H10D84/0135 (20250101);  
H10D84/038 (20250101);

## Field of Classification Search

**CPC:** H01L (27/0629); H01L (21/823418); H01L (21/823437); H01L (27/11521); H01L  
(27/11526); H01L (29/42328); H01L (21/762); H01L (23/528); H01L (27/11534); H01L  
(27/11548); H01L (29/40114)

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## **Background/Summary**

CROSS-REFERENCE TO RELATED APPLICATION (1) The present application is a continuation of U.S. Non-provisional patent application Ser. No. 17/870,415, filed on Jul. 21, 2022, titled “Polysilicon Resistor Structures”, which is a divisional of U.S. Non-provisional patent application Ser. No. 16/549,077, filed on Aug. 23, 2019, titled “Polysilicon Resistor Structures,” and now U.S. Pat. No. 11,456,293. The contents of the aforementioned applications are incorporated by reference herein in its entirety.

### **BACKGROUND**

(1) The operation of integrated circuits (IC) requires a combination of active components (e.g., transistors) and passive components (e.g., resistors, inductors, and capacitors), which can be formed on the same substrate. Resistors are primarily used in an IC as means to control the current flow to other components of the IC—for example, resistors can be used to divide the supply voltage into smaller increments.

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## **Description**

### **BRIEF DESCRIPTION OF THE DRAWINGS**

- (1) 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 common 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.
- (2) FIG. 1 is top down view of a polysilicon resistor structure, in accordance with some embodiments.
- (3) FIG. 2 is an isometric view of a non-silicided polysilicon resistor structure, in accordance with some embodiments.
- (4) FIG. 3 is an isometric view of a silicided polysilicon resistor structure, in accordance with some embodiments.
- (5) FIG. 4 is a cross-sectional view of a non-silicided polysilicon resistor structure, in accordance with some embodiments.
- (6) FIG. 5 is a cross-sectional view of a silicided polysilicon resistor structure, in accordance with some embodiments.
- (7) FIG. 6 is flow chart describing a method for forming silicided and non-silicided polysilicon resistor structures, in accordance with some embodiments.
- (8) FIGS. 7-11 are cross-sectional views describing a fabrication process of silicided and non-silicided polysilicon resistor structures, in accordance with some embodiments.

### **DETAILED DESCRIPTION**

(9) The following disclosure provides 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 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 that are between the first and second features, such that the first and second features are not in direct contact.

(10) 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.

(11) The term “nominal” as used herein refers to a desired, or target, value of a characteristic or parameter for a component or a process operation, set during the design phase of a product or a process, together with a range of values above and/or below the desired value. The range of values is typically due to slight variations in manufacturing processes or tolerances.

(12) In some embodiments, the terms “about” and “substantially” can indicate a value of a given quantity that varies within 5% of the target value (e.g.,  $\pm 1\%$ ,  $\pm 2\%$ ,  $\pm 3\%$ ,  $\pm 4\%$ ,  $\pm 5\%$  of the target value).

(13) The term “vertical,” as used herein, means nominally perpendicular to the surface of a substrate.

(14) A resistor is a passive electrical component used in electronic circuits to, for example, reduce current flow, adjust signal levels, divide voltages, and to bias active elements. In integrated circuits (ICs), resistors can be integrated and formed concurrently with other IC components—such as transistors, memory arrays, capacitors, etc. Important parameters for a resistor in an IC include sheet resistance, value tolerance (e.g., the percentage of error in the resistor's resistance), contribution to parasitic capacitances, temperature coefficient of resistance (TCR), and voltage coefficient of resistance (VCR). For example, TCR and VCR are metrics that can be used to evaluate the stability of the resistor's resistance within a temperature range or within a voltage range, respectively.

(15) In IC manufacturing, metal gate (MG) materials and high-dielectric constant dielectric materials (e.g., high-k dielectric materials (“HK dielectric materials”)) can be used for the fabrication of field effect transistors (FETs). Resistors and FETs can be fabricated concurrently in the IC; as such, MG and HK dielectric materials can be implemented in the resistor's fabrication process to simplify, harmonize, and streamline the manufacturing process between FETs and resistors.

(16) In cases where resistors with higher sheet resistances are required (e.g., sheet resistances greater than about 500  $\Omega$ /square), titanium nitride (TiN) can replace the metal gate material in the resistor structure. This is because resistors with MG material (“MG resistors”) have a sheet resistance range between about 30  $\Omega$ /square and about 130  $\Omega$ /square, while resistors with TiN (“TiN resistors”) have a sheet resistance between about 500  $\Omega$ /square and about 1000  $\Omega$ /square (e.g., one order of magnitude higher). However, the aforementioned types of resistors can suffer from poor current density—for example, MG resistors exhibit a maximum current density (“ $J_{max}$ ”) between about  $0.05 \times W$  and about  $0.5 \times W$  and TiN resistors exhibit a  $J_{max}$  between about  $0.1 \times W$  and about  $1 \times W$  mA, where “W” is the width of the resistor structure.

(17) Embodiments of the present disclosure are directed to a method for forming resistors that combine HK dielectrics and polysilicon to form a polysilicon resistor that exhibits a wider sheet resistance range, higher  $J_{max}$ , and improved performance compared to TiN and MG resistors. The resulting polysilicon resistor can be silicided or non-silicided and can be fabricated alongside devices that use HK/MG materials. In some embodiments, the resulting silicided resistors can have a  $J_{max}$  between about  $1 \times W$  and about  $10 \times W$  mA, and the non-silicided polysilicon resistors can have a  $J_{max}$  between about  $0.1 \times W$  and about  $1 \times W$  mA. Additionally, the silicided and non-

silicided resistors exhibit a lower sheet resistance range when compared to their TiN and MG resistor counterparts. Further, the polysilicon resistors described herein are compatible with fabrication methods used for HK/MG devices.

(18) According to some embodiments, FIG. 1 is a top view of a polysilicon resistor structure **100** having a width **100W** and a length **100L** where a ratio of the resistor's length to the resistor's width is greater than about 1—e.g.,  $100L/100W > 1$ . Polysilicon resistor structure **100** further includes contact regions **105** and **110** with respective contact structures **115** formed thereon. In some embodiments, contact structures **115** include a conductive material such as cobalt (Co) or tungsten (W). Contact structures **115** electrically connect polysilicon resistor structure **100** to other components or areas of the IC and are not shown in FIG. 1 for simplicity. By way of example and not limitation, electric current (“current”) in polysilicon resistor structure **100** flows from contacts **115** in contact region **105** to contact structures **115** in contact region **110**. Current in polysilicon resistor structure **100** flows either through a polysilicon layer or a silicide layer not shown in FIG. 1. Resistor structure **100** is not limited to the depiction of FIG. 1 and fewer or more contact structures **115** are possible. Further, contact structures **115** can have different sizes or shapes. Likewise, contact regions **105** and **110** can be larger or smaller depending on the resistor design and voltage or current requirements.

(19) In some embodiments, the resistance of polysilicon resistor structure **100** can be modulated through its dimensions such as length **100L** and width **100W**. The dimensions of polysilicon resistor structure **100** can be defined via patterning (e.g., via photolithography and etching operations) according to the desired resistance value and other layout considerations (e.g., the minimum pitch to neighboring structures, etc.). In some embodiments, multiple polysilicon resistor structures, like polysilicon resistor structure **100**, with different or similar resistance can be formed throughout the IC.

(20) In some embodiments, FIG. 2 is an isometric view of polysilicon resistor structure **100**. By way of example and not limitation, FIG. 1 can be a top view of polysilicon resistor structure **100**. Even though FIG. 2 does not show contact structures **115** of FIG. 1, FIG. 2 shows other structural elements of polysilicon resistor structure **100**. For example, polysilicon resistor structure **100** is formed on an isolation region **200** embedded in a semiconductor substrate **210**. In some embodiments, isolation region **200** can be a shallow trench isolation region (e.g., an STI region) that includes a dielectric material, such as silicon oxide (SiO<sub>2</sub>) or a low-k dielectric material (e.g., with a k-value lower than about 3.9). Isolation region **200** is formed in semiconductor substrate **210** to provide electrical isolation between doped regions of semiconductor substrate **210**. Isolation region **200** may extend laterally along the x-y plane of FIG. 2. According to some embodiments, semiconductor substrate **210** can include (i) silicon, (ii) a compound semiconductor such as gallium arsenide (GaAs), gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), and/or indium antimonide (InSb), (iii) an alloy semiconductor including silicon germanium (SiGe), gallium arsenide phosphide (GaAsP), aluminum indium arsenide (AlInAs), aluminum gallium arsenide (AlGaAs), gallium indium arsenide (GaInAs), gallium indium phosphide (GaInP), and/or gallium indium arsenide phosphide (GaInAsP), or (iv) combinations thereof. For example purposes, semiconductor substrate **210** will be described in the context of crystalline silicon. Based on the disclosure herein, other materials, as discussed above, can be used. These materials are within the spirit and scope of this disclosure.

(21) Polysilicon resistor structure **100** is laterally isolated from neighboring devices or structures (not shown in FIG. 2) through dielectric layer **220**. In some embodiments, dielectric layer **220** can be an interlayer dielectric such as SiO<sub>2</sub>, doped SiO<sub>2</sub>, or any other suitable dielectric material with a dielectric constant equal to or less than about 3.9 (e.g., about 3.6, about 3.3). By way of example and not limitation, dielectric layer **220** surrounds the side surfaces of polysilicon resistor structure **100** as shown in FIG. 2.

(22) In some embodiments, polysilicon resistor structure **100** includes a stack of (i) a HK dielectric

layer **230** formed on isolation region **200**, (ii) a metal nitride layer **240** formed on HK dielectric layer **230**, and (iii) a polysilicon layer **250** formed on metal nitride layer **240**. By way of example and not limitation, HK dielectric layer **230** can include a metal oxide, such as hafnium oxide, with a dielectric constant (k-value) greater than about 3.9 (e.g., between about 4.0 and about 40). In some embodiments, HK dielectric layer **230** has a thickness between about 2 Å and about 100 Å (e.g., between about 2 Å and about 10 Å, between about 6 Å and about 20 Å, between about 10 Å and about 30 Å, between about 15 Å and about 40 Å, between about 35 Å and about 60 Å, between about 45 Å and about 80 Å, and between about 70 Å and about 100 Å). By way of example and not limitation, metal nitride layer **240** can include titanium nitride and can have a thickness between about 10 Å and 1000 Å (e.g., between about 10 Å and about 100 Å, between about 60 Å and about 200 Å, between about 150 Å and about 300 Å, between about 270 Å and about 500 Å, between about 450 Å and about 800 Å, between about 500 Å and about 950 Å, and between about 750 Å and about 1000 Å). In some embodiments, polysilicon layer **250** has a thickness **250T** that ranges between about 10 nm and about 300 nm (e.g., between about 10 nm and about 100 nm, between about 50 nm and about 200 nm, and between about 150 nm and about 300 nm).

(23) Further, polysilicon resistor structure **100** includes spacer structures **260** on its sidewalls along its length **100L** as shown in FIG. 2 (but not shown in FIG. 1 for simplicity). By way of example and not limitation, spacer structures **260** can include a nitride, such as silicon nitride, and may include one or more layers.

(24) In some embodiments, polysilicon layer **250** includes silicided portions **270**, which define contact regions **105** and **110** where contact structures (e.g., contact structures **115** shown in FIG. 1) are formed. In some embodiments, silicided portions **270** are cladding silicide layers spaced apart and located on opposite ends of polysilicon resistor structure **100** as shown in FIG. 2. In some embodiments, the entire top surface of polysilicon layer **250** can be silicided as shown for polysilicon resistor structure **300** in FIG. 3.

(25) In some embodiments, polysilicon layer **250** includes a top doped layer and an underlying bottom intrinsic (e.g., un-doped) layer, which is in direct contact with metal nitride layer **240**. For example, FIG. 4 is a cross-sectional view of FIG. 2 along cut line AB where polysilicon layer **250** is shown to have a top doped layer **250A** and a bottom intrinsic (un-doped) layer **250B**. Here, polysilicon layer **250** is referred to as “partially doped” because top doped layer **250A** is thinner than thickness **250T** of polysilicon layer **250**. In some embodiments, the thickness of top doped layer **250A** is equal to or greater than about 50 Å when measured from the top surface of polysilicon layer **250**. If doped layer **250A** is thinner than about 50 Å, the resistance of resistor structure **100** may be unacceptably high. In some embodiments, the entire thickness **250T** of polysilicon layer **250** (e.g., between about 10 nm and about 300 nm) is doped—e.g., the thickness of the bottom intrinsic layer **250B** can be nominally zero when polysilicon layer **250** is uniformly doped. In this case, polysilicon layer **250** is referred to as “fully doped.”

(26) In some embodiments polysilicon layer **250** can be doped via an implant process. By way of example and not limitation, polysilicon layer **250** can be doped during the process of forming source/drain regions in transistor devices. By way of example and not limitation, a sacrificial hard mask layer (not shown in FIG. 4) can be formed on the top surface of polysilicon layer **250** to modulate the implant depth and thus the thickness of top doped layer **250A**. For example, the thickness of the resulting doped layer **250A** can be inversely proportional to the thickness of the sacrificial hard mask layer. The hard mask layer can be, for example, a stacked layer of silicon oxide and silicon nitride. In some embodiments, the thickness of top doped layer **250A** can be modulated through implant process conditions (e.g., the implant energy). In some embodiments, the dopant dose for top doped layer **250A** can range from about  $1 \times 10^{12}$  cm.<sup>sup.</sup>-2 to about  $5 \times 10^{16}$  cm.<sup>sup.</sup>-2 and the dopant species can include either n-type (e.g., phosphorous, arsenic, or antimony) or p-type (e.g., boron, indium, or gallium).

(27) FIG. 4 further includes contact structures **115** in physical contact with silicided portions **270** of

polysilicon layer **250**. By way of example and not limitation, contact structures **115** include a conductive material, such as tungsten or cobalt. Additionally, contact structures **115** are embedded in a dielectric layer **400**. In some embodiments, dielectric layer **400** is an interlayer dielectric (ILD) that includes un-doped silicate glass (USG), phosphosilicate glass (PSG), borophosphosilicate glass (BPSG), a low-k dielectric (e.g., with a k-value lower than about 3.9), or combinations thereof.

(28) According to some embodiments, during the resistor's operation, electric current **410** ("current **410**") passes through top doped layer **250A** of polysilicon layer **250** along the resistor's length **100L** as shown in FIG. 4. Current **410** enters and exits the resistor structure through contact structures **115**. According to some embodiments, the electrical contact formed between contact structures **115** and silicided portions **270** has negligible resistance compared to the total resistance of resistor structure **100**.

(29) According to some embodiments, the resistance of resistor structure **100** can be modulated. By way of example and not limitation, the resistance of resistor structure **100** can be based on (i) the dopant concentration of top doped layer **250A**, (ii) the thickness of top doped layer **250A**, (iii) the length **100L** and/or width **100W** of resistor structure **100** shown in FIGS. 1 and 2, or (iv) combinations thereof. In some embodiments, for a fixed dopant concentration and thickness for top doped layer **250A**, the resistance of resistor structure **100** can be modulated through the structure's physical dimensions (e.g., **100L** and/or **100W**). In some embodiments, the physical dimensions of resistor structure **100** can be defined by patterning—e.g., by photolithography and etching operations.

(30) FIG. 5 is a cross sectional view of polysilicon resistor structure **300** across cut line CD shown in FIG. 3. Polysilicon resistor structure **300** shown in FIGS. 3 and 5 differs from polysilicon resistor structure **100** shown in FIGS. 2 and 4 in that the entire top surface of polysilicon layer **250** is silicided. In other words, silicided portion **270** in polysilicon resistor structure **300** covers the entire surface of polysilicon layer **240**. In some embodiments, another difference between polysilicon resistor structures **100** and **300** is their operation. For example, resistor structure **100** operates by flowing current **410** through top doped layer **250A** of polysilicon layer **250**, while resistor structure **300** operates by flowing current **410** through silicided portion **270** of polysilicon layer **250**. Consequently, polysilicon resistor structures **100** and **300** have different electrical characteristics (e.g., resistance and current density ratings). In some embodiments, polysilicon resistor structure **100** is referred to as a "non-silicided polysilicon resistor" and polysilicon resistor structure **300** is referred to as a "silicided polysilicon resistor." In some embodiments, silicided polysilicon resistors (e.g., polysilicon resistor structure **300**) can be combined with non-silicided polysilicon resistors (e.g., polysilicon resistor structure **100**) in the same IC. For example, silicided polysilicon resistors (e.g., polysilicon resistor structure **300**) and non-silicided polysilicon resistors (e.g., polysilicon resistor structure **100**) can be formed on the same substrate depending on the resistance and current density requirements of the IC.

(31) The silicide material in silicided portions **270** of polysilicon resistor structures **100** and **300** can be the same or different. By way of example and not limitation, the silicide material can be nickel silicide, cobalt silicide, tungsten silicide, titanium silicide, or any other suitable silicide material. In some embodiments, the thickness of silicided portion **270** in resistor structure **300** shown in FIGS. 3 and 5 ranges between about 50 Å and about 2000 Å.

(32) Similar to polysilicon resistor structure **100**, polysilicon resistor structure **300** can include a partially-doped or a fully-doped polysilicon layer **250**. In other words, polysilicon layer **250** can have a top doped layer **250A** that extends partially in polysilicon layer **250** or occupies the entire thickness **250T** of polysilicon layer **250** shown in FIG. 3.

(33) In some embodiments, polysilicon resistor structures **100** and **300** can be formed in a logic device area of an IC and share common fabrication operations with memory and/or logic device structures. For example, polysilicon layer **250** can be formed when sacrificial polysilicon gate structures are formed in logic devices (e.g., FETs). Further, polysilicon layer **250** can be doped

during the process of forming source-drain regions in the memory array and/or the logic device areas of the IC. In another example, silicided portion **270** of polysilicon layer **250** can be formed concurrently with a silicidation process performed for the polysilicon gates of transistors in the memory array. In other words, in some embodiments, the formation process of polysilicon resistor structures **100** and **300** can be integrated with the formation process of memory array and logic device structures without the need for additional manufacturing operations.

(34) In some embodiments, non-silicided polysilicon resistors, like polysilicon resistor structure **100**, has a sheet resistance between about 500  $\Omega$ /square and about 1000  $\Omega$ /square for a p-type doped polysilicon layer and between about 100  $\Omega$ /square and about 500  $\Omega$ /square for an n-type doped polysilicon layer. In some embodiments, silicided polysilicon resistors, like polysilicon resistor structure **300**, can have a sheet resistance between about 1  $\Omega$ /square and about 50  $\Omega$ /square for a p-type doped polysilicon layer and between about 1  $\Omega$ /square and about 50  $\Omega$ /square for an n-type doped polysilicon layer. In some embodiments, the silicided polysilicon resistors have a lower sheet resistance compared to the non-silicided polysilicon resistors. As a result, the maximum current density (current carrying capability) for each type of polysilicon resistor (e.g., silicided or non-silicided) can be different. For example, the maximum current density ( $J_{max}$ ) for a non-silicided polysilicon resistor can range between about  $0.1 \times W$  and about  $1 \times W$  mA and for a silicided polysilicon resistor can range between about  $1 \times W$  and about  $10 \times W$  mA, where  $W$  is the width of the resistor structure (e.g., 100 W and 300 W shown in FIGS. 2 and 3, respectively). According to some embodiments, both polysilicon resistors types (e.g., non-silicided and silicided) exhibit maximum current density ( $J_{max}$ ) values with limited temperature dependency compared to MG and TiN resistors. For example, both polysilicon resistor types can carry a large percentage of their maximum current density ( $J_{max}$ ) for a wide range of temperatures. By way of example and not limitation, a polysilicon resistor operated at 110° C. exhibits a  $J_{max}$  that is about 1 to about 10% lower than its  $J_{max}$  value when operated at 125° C. In comparison, the MG and TiN resistors operated at 110° C. exhibit a  $J_{max}$  that is about 30% to about 90% lower than their  $J_{max}$  value when operated at 125° C.

(35) FIG. 6 is a flow chart of a method **600** for forming non-silicided and silicided polysilicon resistors. Other fabrication operations may be performed between the various operations of method **600** and may be omitted merely for clarity. Embodiments of the present disclosure are not limited to method **600**. Method **600** will be described in reference to FIGS. 1-5 and 7-11.

(36) In referring to FIG. 6, method **600** begins with operation **610** and the deposition of a resistor stack with a HK layer, a metal nitride layer, and a polysilicon layer. The resistor stack of operation **610** includes the same layers with polysilicon resistors structures **100** and **300** shown in FIGS. 2-5—for example, HK layer **230**, metal nitride layer **240**, and polysilicon layer **250**. In operation **610**, the resistor stack can be blanket deposited over the semiconductor substrate. For example, FIG. 7 is a cross-sectional view along cut lines A'B' and C'D' of FIGS. 2 and 3 respectively and shows a resistor stack **700** blanket deposited over semiconductor substrate **210** according to operation **610**. In some embodiments, semiconductor substrate **210** includes additional isolation region(s) **710**. In some embodiments, isolation region(s) **710** are filled with dielectric material that can be different from the dielectric material in isolation region **200**. By way of example and not limitation, isolation region **200** can include a low-k dielectric material (e.g., a material with a k-value less than about 3.9), while isolation region(s) **710** can include a silicon oxide with a k-value substantially equal to about 3.9.

(37) In some embodiments, prior to depositing HK layer **230**, an interfacial layer **720** is grown on semiconductor substrate **210** to improve the interface quality between semiconductor substrate **210** and the deposited HK layer **230**. In some embodiments, interfacial layer **720** includes a silicon dioxide layer with a thickness between about 3 Å and about 30 Å.

(38) In some embodiments, a hard mask layer **730** is deposited over the resistor stack **700**, as shown in FIG. 7. Hard mask layer **730** can be silicon oxide, silicon nitride, other suitable



dielectrics, or combinations thereof. In some embodiments, hard mask layer **730** protects the underlying layers during subsequent processing.

(39) In referring to FIGS. **6** and **8**, method **600** continues with operation **610** and the patterning of resistor stack **700** to form a polysilicon resistor structure **800**. In some embodiments, patterning of resistor stack **700** is accomplished via photolithography and etching operations. During the patterning process of operation **610**, the physical dimensions of polysilicon resistor structure **800**—for example, width **800W** and a length dimension (not shown in FIG. **8**)—can be defined as discussed above with respect to polysilicon resistor structures **100** and **300** in FIGS. **2** and **3**.

(40) In some embodiments, alongside polysilicon resistor structure **800**, transistor structure **810** can be formed on semiconductor substrate **210** and between isolation regions **200** and **710** as shown in FIG. **8**. The physical dimensions of transistor structure **810** can be independent from the physical dimensions of polysilicon resistor structure **800**. In other words, the design rules governing transistor structures **810** and polysilicon resistor structure **800** can be different. This is because transistor structure **810** is an active device with different functionality than polysilicon resistor structure **800**. Further, additional devices (e.g., transistors and capacitors) or arrays (e.g., memory arrays) may be formed in other areas of semiconductor substrate **210** either prior to or during the process of forming polysilicon resistor structure **800** and transistor structure **810**. These other structures are not shown in FIG. **8** for simplicity and are within the spirit and the scope of this disclosure.

(41) In some embodiments, multiple resistor structures, like polysilicon resistor structure **800**, can be “defined” (formed) during the patterning process described in operation **620**. Further, not all the polysilicon resistor structures formed according to method **600** may have the same physical dimensions.

(42) In some embodiments, lightly doped implants may be used to form the source-drain extension regions of transistor structure **810**. These extension regions are not shown in FIG. **8** for simplicity. According to some embodiments, spacer structures **260** are formed on sidewall surfaces of polysilicon resistor structure **800** and transistor structures **810**, as shown in FIG. **8**. By way of example and not limitation, spacer structures **260** can be formed by a blanket deposition of a spacer material (e.g., silicon nitride) followed by an anisotropic etching process that selectively removes the spacer material from horizontal surfaces of the structures shown in FIG. **8**.

(43) In referring to FIG. **6**, method **600** continues with operation **630** where polysilicon layer **250** of polysilicon resistor structure **800** is implanted with dopants to form a top doped layer **250A**. In some embodiments, referring to FIG. **8** and during the implant process described in operation **630**, source-drain regions of transistor structure **810** can be formed in semiconductor substrate **210** adjacent to spacer structures **260**. In other words, during operation **630**, top doped layer **250A** in polysilicon resistor structure **800** and source-drain regions **820** in transistor structure **810** are concurrently formed. As a result, source-drain regions **820** and top doped layer **250A** can share the same type of dopants (e.g., n-type or p-type). According to some embodiments, a benefit of operation **630** is that top doped layer **250A** in a resistor structure and source-drain regions **820** in a transistor structure are formed from a single operation (operation **630**). This eliminates the need for independent processing operations to form top doped layer **250A** and source-drain regions **820**.

(44) In some embodiments, the thickness of top doped layer **250A** when measured from a top surface of polysilicon layer **250** is between about 5 nm and about 200 nm or about the total thickness (**250T**) of polysilicon layer **250**—which can range from about 10 nm to about 300 nm (e.g., between about 10 nm and about 100 nm, between about 50 nm and about 200 nm, and between about 150 nm and about 300 nm).

(45) According to some embodiments, a silicide **830** can be formed on source-drain regions **820** of transistor structure **810**. Silicide **830** can be formed, for example, by blanket depositing a metal (e.g., titanium, nickel, cobalt, tungsten, etc.) and subsequently annealing semiconductor substrate **210** to initiate the silicidation reaction between the deposited metal and the semiconductor material

(e.g., silicon) in source-drain regions **820**. Any un-reacted metal can be removed with a wet etching process.

(46) In some embodiments, as shown in FIG. **9**, hard mask layer **730** is removed from polysilicon resistor structure **800** and transistor structure **810**, and an etch stop layer **900** can be formed over polysilicon resistor structure **800** and transistor structure **810**. Etch stop layer **900** can extend over isolation regions **200/710**, source-drain regions **820**, and exposed portions of semiconductor substrate **210**. In some embodiments, etch stop layer **900** can cover other structures (e.g., memory arrays) on semiconductor substrate **210** not shown in FIG. **9**. It is noted that etch stop layer **900** is not shown in FIGS. **2** and **3** for simplicity.

(47) In referring to FIG. **6**, method **600** continues with operation **640** and the process of forming a dielectric layer around polysilicon resistor structure **800**. In some embodiments, the dielectric layer of operation **640** is dielectric layer **220** shown in FIGS. **2-5**. By way of example and not limitation, the dielectric layer (e.g., dielectric layer **220**) can be formed by blanket depositing a dielectric material over polysilicon resistor structure **800**, transistor structure **810**, isolation regions **200/710**, source-drain regions **820**, and exposed portions of semiconductor substrate **210**. In some embodiments, the dielectric layer can cover other structures (e.g., memory arrays) on semiconductor substrate **210** not shown in FIG. **10**. As shown in FIG. **10**, a chemical mechanical polishing (CMP) process can be subsequently used to planarize and remove excess dielectric material from the top of polysilicon resistor structure **800** and transistor structure **810**. In some embodiments, etch stop layer **900** acts a stopping layer for the CMP process of operation **640**.

(48) In a subsequent operation, semiconductor material **250** in transistor structure **810** is removed and replaced by a metal gate electrode **1000**. In some embodiments, metal gate electrode **1000** includes one or more metallic layers.

(49) In referring to FIGS. **6** and **10**, method **600** continues with operation **650** where a silicide **1010** is formed on the top surface of polysilicon layer **250** of polysilicon resistor structure **800**.

According to some embodiments, the surface area of silicide **1010** corresponds to silicided portions **270** shown in FIGS. **2** and **3**. As discussed above with respect to FIGS. **2** and **3**, silicided portions **270** may extend to the entire surface of polysilicon layer **250** as shown in FIG. **3** to form a silicided polysilicon resistor structure **800**. In some embodiments, silicide **1010** is restricted to the “edges” of the resistor structure, as shown in FIG. **2**, resulting in a non-silicided polysilicon resistor structure **800**. If a non-silicided resistor structure is desired, like resistor structure **100** in FIG. **2**, the “not-to-be silicided portions” of top polysilicon layer **250** can be covered with a mask layer (e.g., an oxide or nitride) prior to the silicidation process. If a silicided resistor structure is desired, like resistor structure **300** in FIG. **3**, polysilicon layer **250** may be exposed during the silicidation process.

(50) The silicidation process can be similar to the silicidation process described above for the source-drain regions **820**. In some embodiments, during the silicidation process of operation **650**, other structures on semiconductor substrate **210** may also be silicided. For example, polysilicon gate structures in memory arrays, like in non-volatile memory arrays such as embedded flash memory arrays, can also be silicided concurrently with the resistor structures. This eliminates the need for independent silicidation processes for the process of forming silicide **1010** in polysilicon resistor structure **800** and on other structures on semiconductor substrate **210**.

(51) In referring to FIGS. **6** and **11**, method **600** continues with operation **660** and the process of forming a contact on polysilicon resistor structure **800**. This can be accomplished by depositing another dielectric layer, like dielectric layer **400** shown in FIGS. **4** and **5**, over dielectric layer **220**. In some embodiments, the dielectric layer of operation **660** (e.g., dielectric layer **400**) is blanket deposited over the structures on semiconductor substrate **210** and it is subsequently planarized as shown in FIG. **11**. Next, dielectric layer **400** is etched to form a contact opening that partially exposes silicide **1010** of polysilicon resistor structure **800**. A conductive material is deposited to fill the etched opening. Excess conductive material on the top surface of dielectric layer **400** is

subsequently planarized to form contact structure **115** shown in FIG. **11**.

(52) In some embodiments, more than one contact structure **115** can be formed concurrently on polysilicon resistor structure **800** as shown in FIG. **1**. Further, contact structure **115** is aligned and physically connected to a silicided portion **270** of polysilicon layer **250** shown in FIGS. **2-5**. This ensures a low contact resistance between contact structure **115** and polysilicon resistor structure **800**. According to some embodiments, additional contacts can be formed on other structures of the IC including contacts to source-drain regions **820**, contacts to metal gate electrode **1000**, and contact to other structures not shown in FIG. **11**, such as memory arrays, capacitor structures, etc.

(53) Embodiments of the present disclosure are directed to a method for forming polysilicon resistors that combine HK dielectrics and polysilicon. These polysilicon resistors can be silicided or non-silicided, exhibit a wider sheet resistance range, and a higher current density capability over a wider range of temperatures compared to MG and TiN resistors. The resulting polysilicon resistors, according to the embodiments described herein, can be fabricated at a low cost without substantial changes to the fabrication process alongside with HK/MG FETs and other devices—such as memory arrays. In some embodiments, the resulting silicided and non-silicided polysilicon resistors offer a current density between about  $1 \times W$  and about  $10 \times W$  mA and between about  $0.1 \times W$  and about  $1 \times W$  mA respectively, where  $W$  is the width of the resistor structure. Further, the polysilicon resistors described herein are compatible with fabrications methods used for HK/MG devices.

(54) In some embodiments, a semiconductor structure includes a semiconductor substrate with spaced apart first and second isolation regions formed therein, where the first isolation region is wider than the second isolation region. The semiconductor structure further includes a resistor structure disposed on the first isolation region, where the resistor structure includes a dielectric layer in contact with the first isolation region, a nitride layer disposed on the dielectric layer, and a semiconductor layer disposed on the nitride layer that includes a doped top portion with a silicide portion formed on opposite ends of the doped top portion. The semiconductor structure also includes a transistor structure disposed between the first and second isolation regions. The transistor structure includes an interfacial layer in contact with the substrate, where the dielectric layer is disposed on the interfacial layer and the nitride layer is disposed on the dielectric layer; a metal gate electrode disposed on the nitride layer; and a source/drain region formed in the substrate and adjacent to the metal gate electrode.

(55) In some embodiments, a method includes depositing a resistor stack on a substrate that includes spaced apart first and second isolation regions, where depositing the resistor stack includes depositing a metal oxide dielectric layer on the substrate, depositing a metal nitride layer on the metal oxide dielectric layer, and depositing a polysilicon layer on the metal nitride layer. Further the method includes patterning the resistor stack to form a polysilicon resistor structure on the first isolation region and a gate structure between the first and second isolation regions, and doping the polysilicon resistor structure to form a doped layer in the polysilicon layer of the polysilicon resistor structure and source-drain regions in the substrate adjacent to the gate structure. Also, the method includes forming a dielectric layer between the polysilicon resistor and gate structures, replacing the polysilicon layer in the gate structure with a metal gate electrode to form a transistor structure with the gate structure and the source-drain regions, and forming a silicide on the doped layer of the polysilicon layer in the polysilicon transistor structure.

(56) In some embodiments, a structure includes a substrate comprising spaced apart first and second isolation regions, a polysilicon resistor on the first isolation region, where the polysilicon resistor includes a metal oxide dielectric layer, a metal nitride layer, and a polysilicon layer having a top surface with a silicided portion. Further the structure includes a transistor structure formed between the first and second isolation regions, where the transistor structure includes the metal oxide dielectric layer, the metal nitride layer, and a metal gate electrode. The structure also includes one or more contacts on the silicided portion of the polysilicon layer.

(57) It is to be appreciated that the Detailed Description section, and not the Abstract of the

Disclosure section, is intended to be used to interpret the claims. The Abstract of the Disclosure section may set forth one or more but not all possible embodiments of the present disclosure as contemplated by the inventor(s), and thus, are not intended to limit the subjoined claims in any way.

(58) The foregoing disclosure 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 will 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 will 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. A method, comprising: forming a resistor stack on a substrate, comprising: forming a dielectric layer on the substrate; forming a metal nitride layer on the dielectric layer; and forming a polysilicon layer on the metal nitride layer; patterning the resistor stack to form a resistor structure; doping an upper portion of the polysilicon layer to form a doped polysilicon layer; forming a silicide layer covering an entire top surface of the doped polysilicon layer; and forming a contact structure on the silicide layer to direct current through the resistor structure along a length of the resistor structure.
2. The method of claim 1, wherein doping the upper portion of the polysilicon layer comprises ion implanting the upper portion of the polysilicon layer with an n-type dopant or a p-type dopant.
3. The method of claim 2, wherein doping the upper portion of the polysilicon layer further comprises: forming a sacrificial hard mask layer on the polysilicon layer; and controlling a depth of the doped polysilicon layer by modulating a thickness of the sacrificial hard mask layer.
4. The method of claim 1, wherein forming the silicide layer comprises: depositing a metal layer on the doped polysilicon layer; and annealing the metal layer to form the silicide layer.
5. A method, comprising: forming, on a substrate, a polysilicon resistor stack structure concurrently with a transistor, wherein forming the polysilicon resistor stack structure comprises: forming a dielectric layer on the substrate; forming a metal nitride layer on the dielectric layer; and forming a polysilicon layer on the metal nitride layer; simultaneously doping the polysilicon layer and a source/drain region of the transistor; and siliciding an entire top surface of the doped polysilicon layer to form a silicide layer.
6. The method of claim 5, wherein doping the polysilicon layer comprises forming a doped polysilicon layer and an un-doped polysilicon layer within the polysilicon layer.
7. The method of claim 5, wherein doping the polysilicon layer comprises forming a fully-doped polysilicon layer.
8. The method of claim 5, further comprising patterning the polysilicon resistor stack structure to form a polysilicon resistor structure.
9. The method of claim 8, further comprising forming a dielectric layer surrounding the polysilicon resistor structure and the transistor.
10. The method of claim 5, further comprising forming a contact structure on the silicide layer.
11. The method of claim 5, wherein simultaneously doping the polysilicon layer and the source/drain region of the transistor comprises doping the polysilicon layer and the source/drain region of the transistor with a same dopant species.
12. A method comprising: forming a stacked polysilicon resistor on a substrate, the stacked polysilicon resistor comprising: a doped polysilicon layer disposed on an un-doped polysilicon layer; and a silicide layer disposed on the doped polysilicon layer; forming a sidewall spacer in

contact with the stacked polysilicon resistor; and forming a contact structure on the silicide layer.

13. The method of claim 12, wherein forming the doped polysilicon layer comprises forming the doped polysilicon layer at a depth of about 5 nm and about 200 nm from a top surface of the polysilicon layer.

14. The method of claim 12, further comprising forming an etch stop layer surrounding the sidewall spacer.

15. The method of claim 12, further comprising forming a first dielectric layer surrounding the stacked polysilicon resistor.

16. The method of claim 15, further comprising forming a second dielectric layer on the first dielectric layer.

17. The method of claim 1, further comprising forming spacer structures on sidewall surfaces of the resistor stack.

18. The method of claim 17, further comprising forming an etch stop layer surrounding the spacer structures.

19. The method of claim 5, further comprising forming spacer structures on sidewall surfaces of the polysilicon resistor stack structure.

20. The method of claim 19, further comprising forming an etch stop layer surrounding spacer structures.

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