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SEMICONDUCTOR DEVICES INCLUDING GATE SPACER

Abstract

A semiconductor device includes a first active region defined on a substrate, a first gate electrode across the first active region, a first drain region in the first active region at a position adjacent to the first gate electrode, an undercut region between the first active region and the first gate electrode, and a first gate spacer on a side surface of the first gate electrode and extending into the undercut region.

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Background/Summary

CROSS-REFERENCE TO THE RELATED APPLICATION [0001] This application is a continuation of U.S. application Ser. No. 18/483,413, filed Oct. 9, 2023, which is a continuation of U.S. application Ser. No. 17/060,193, filed Oct. 1, 2020, now U.S. Pat. No. 11,810,964, which claims priority to Korean Patent Application No. 10-2020-0042140, filed on Apr. 7, 2020, in the Korean Intellectual Property Office, and entitled: “Semiconductor Devices Including Gate Spacer,” is incorporated by reference herein in their entireties.

BACKGROUND

1. Field

[0002] The disclosure relates to semiconductor devices including a gate spacer and a method of forming the same.

2. Description of the Related Art

[0003] With the trend of high integration of semiconductor devices, technology using a gate spacer and a replacement gate electrode has been developed. The shape of the gate spacer has a great influence on the process of forming the replacement gate electrode.

SUMMARY

[0004] A semiconductor device in accordance with an exemplary embodiment of the disclosure may include a first active region defined on a substrate. A first gate electrode may be disposed across the first active region thereon. A first drain region may be disposed in the first active region at a position adjacent to the first gate electrode. An undercut region may be disposed between the first active region and the first gate electrode. A first gate spacer may be disposed on a side surface of the first gate electrode, and may extend in the undercut region.

[0005] A semiconductor device in accordance with an exemplary embodiment of the disclosure may include a first active region defined in a first region on a substrate. A first gate electrode may be disposed across the first active region thereon. A first drain region may be disposed in the first active region at a position adjacent to the first gate electrode. A first gate spacer may be disposed on a side surface of the first gate electrode. A second active region may be defined in a second region on the substrate. A second gate electrode may be disposed across the second active region thereon, and may have a different horizontal width from the first gate electrode. A second drain region may be disposed in the second active region at a position adjacent to the second gate electrode. A lower gate dielectric layer may be disposed between the second active region and the second gate electrode, and may have a smaller width than the second gate electrode. A second gate spacer may be disposed on a side surface of the second gate electrode, and may extend in an undercut region between the second active region and the second gate electrode. The second gate spacer may be in contact with a side surface of the lower gate dielectric layer.

[0006] A semiconductor device in accordance with an exemplary embodiment of the disclosure

may include a first active region defined in a first region on a substrate. A first gate electrode may be disposed across the first active region thereon. A first gate dielectric layer may be disposed between the first active region and the first gate electrode. A pair of first drain regions may be disposed in the first active region at positions adjacent to opposite sides of the first gate electrodes, and may be spaced apart from each other. An undercut region may be disposed between the first active region and the first gate electrode. A first gate spacer may be disposed on a side surface of the first gate electrode, and may extend in the undercut region. A second active region may be defined in the second region on the substrate. A second gate electrode may be disposed across the second active region thereon, and may have a larger horizontal width than the first gate electrode. A second gate dielectric layer may be disposed between the second active region and the second gate electrode. A pair of second drain regions may be disposed in the second active region at positions adjacent to opposite sides of the second gate electrodes, and may be spaced apart from each other. A lower gate dielectric layer may be disposed between the second active region and the second gate dielectric layer, and may have a larger horizontal width than the second gate electrode. A second gate spacer may be disposed on a side surface of the second gate electrode. The first active region may include a plurality of channel regions. Each of the plurality of channel regions may be in contact with the pair of first drain regions. The first gate electrode may surround a top surface, a side surface, and a bottom surface of at least one of the plurality of channel regions. The second gate electrode may be disposed on a top surface and a side surface of the second active region. The lower end of the second gate electrode may be disposed at a lower level than the upper end of the second active region.

[0007] A method of forming a semiconductor device in accordance with an exemplary embodiment of the disclosure may include defining a first active region and a second active region on a substrate. A first gate electrode may be formed across the first active region thereon, and a second gate electrode may be formed across the second active region thereon. A first drain region may be formed in the first active region at a position adjacent to the first gate electrode, and a second drain region may be formed in the second active region at a position adjacent to the second gate electrode. A first gate spacer may be formed on a side surface of the first gate electrode. A lower gate dielectric layer may be formed between the second active region and the second gate electrode. A second gate spacer may be formed on a side surface of the second gate electrode. The first gate spacer may extend in an undercut region between the first active region and the first gate electrode.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Features will become apparent to those of skill in the art by describing in detail exemplary embodiments with reference to the attached drawings, in which:

[0009] FIG. 1 is a cross-sectional view illustrating semiconductor devices according to exemplary embodiments of the disclosure.

[0010] FIG. 2 is a layout illustrating semiconductor devices according to exemplary embodiments of the disclosure.

[0011] FIGS. 3 to 5 are enlarged views of parts shown in FIG. 1.

[0012] FIGS. 6 to 13 are cross-sectional views illustrating semiconductor devices according to exemplary embodiments of the disclosure.

[0013] FIGS. 14 to 57 are cross-sectional views of stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure.

DETAILED DESCRIPTION

[0014] FIG. 1 is a cross-sectional view illustrating semiconductor devices according to exemplary

embodiments of the disclosure, and FIG. 2 is a layout illustrating semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 3 to 5 are enlarged views of parts shown in FIG. 1. FIG. 1 illustrates cross-sectional views taken along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2. Semiconductor devices according to exemplary embodiments of the disclosure may include MBCFET®, finFET, or a combination thereof.

[0015] Referring to FIG. 1, semiconductor devices according to exemplary embodiments of the disclosure may include a substrate 20, a first active region 21, a second active region 22, a device isolation layer 25, a lower gate dielectric layer 28, a first gate spacer 41, a second gate spacer 42, a plurality of first drain regions 47, a plurality of second drain regions 48, an interlayer insulating layer 49, a first gate dielectric layer 53, a second gate dielectric layer 54, a plurality of first gate electrodes 55, and a plurality of second gate electrodes 56.

[0016] The first active region 21 may include a plurality of channel regions 21A, 21B, 21C and 21D. The plurality of channel regions 21A, 21B, 21C and 21D may include a first channel region 21A, a second channel region 21B, a third channel region 21C, and a fourth channel region 21D. The first gate spacer 41 may include a first inner spacer 41A and a first outer spacer 41B. The second gate spacer 42 may include a second inner spacer 42A and a second outer spacer 42B. Each of the plurality of first drain regions 47 may include a first layer 47A and a second layer 47B. Each of the plurality of second drain regions 48 may include a third layer 48A and a fourth layer 48B.

[0017] Referring to FIG. 2, the substrate 20 may be provided to have a first region 11 and a second region 12 that is adjacent to the first region 11. The first active region 21 may be disposed in the first region 11 on the substrate 20. The second active region 22 may be disposed in the second region 12 on the substrate 20. The plurality of first gate electrodes 55 may be disposed across the first active region 21 in the first region 11. The plurality of second gate electrodes 56 may be disposed across the second active region 22 in the second region 12.

[0018] Each of the plurality of second gate electrodes 56 may have a different horizontal width from each of the plurality of first gate electrodes 55. Each of the plurality of second gate electrodes 56 may have a larger horizontal width than each of the plurality of first gate electrodes 55. Each of the plurality of first gate electrodes 55 may have a first width W1. Each of the plurality of second gate electrodes 56 may have a second width W2. The second width W2 may be larger than the first width W1.

[0019] Referring to FIG. 3, which illustrates an enlarged portion of FIG. 1 along line 1-1', the first gate dielectric layer 53 may be disposed between the first gate electrode 55 and the plurality of channel regions 21A, 21B, 21C and 21D. The first gate dielectric layer 53 may extend between the first gate electrode 55 and the first gate spacer 41. An interfacial dielectric layer 51 may be disposed between the first gate dielectric layer 53 and the plurality of channel regions 21A, 21B, 21C and 21D. The interfacial dielectric layer 51 may include silicon oxide formed through a thermal oxidation process or a cleaning process. The interfacial dielectric layer 51 may be omitted. In an exemplary embodiment, the first gate dielectric layer 53 may be interposed between the first gate electrode 55 and the interfacial dielectric layer 51.

[0020] A pair of first drain regions 47 may be disposed in the first active region 21 at positions adjacent to opposite sides of the first gate electrode 55. The pair of first drain regions 47 may be spaced apart from each other. Each of the plurality of channel regions 21A, 21B, 21C and 21D may be in contact with the pair of first drain regions 47.

[0021] A first undercut region UC1 may be disposed between the first active region 21 and the first gate electrode 55. For example, as illustrated in FIG. 3, a bottom of the first gate electrode 55 may have a stair profile at bottom corners thereof, e.g., a center portion of the bottom of the first gate electrode 55 may extend deeper than edge portions of the bottom of the first gate electrode 55 to define the stair profile, such that the undercut region UC1 may be defined under the edge portions of the bottom of the first gate electrode 55.

[0022] The first gate spacer 41 may include the first inner spacer 41A and the first outer spacer

41B. The first inner spacer **41A** may include an upper portion **411**, which is disposed on the side surface of the first gate electrode **55**, and a lower portion **412**, which extends, e.g., continuously, from the lower end of the first upper portion **411** into the first undercut region **UC1**. The lower portion **412** may extend between the first active region **21** and the first gate electrode **55**, e.g., between the first active region **21** and the edge portion of the bottom of the first gate electrode **55**. A straight line, e.g., an imaginary straight line, that extends along the outermost side surface of the first gate electrode **55** and is perpendicular to the surface of the substrate **20** may intersect the lower portion **412**. The upper portion **411** may have a height greater than the horizontal width thereof. The lower portion **412** may have a horizontal width greater than the height thereof, e.g., the upper and lower portions **411** and **412** may have a combined cross-section of an inverted “T” that extends along the outermost side surface of the first gate electrode **55** and protrudes into the first undercut region **UC1** to partially overlap the edge portion of the bottom of the first gate electrode **55**. [0023] The first gate dielectric layer **53** may be interposed between the first gate electrode **55** and the upper portion **411** and between the first gate electrode **55** and the lower portion **412**. The first gate dielectric layer **53** may be in contact with the side and top surfaces of the lower portion **412**. The first gate dielectric layer **53** may be in contact with the side surface of the upper portion **411**, e.g., the first gate dielectric layer **53** may be conformal on outer surfaces of the first gate electrode **55**.

[0024] Referring to FIG. 4, which illustrates an enlarged portion of FIG. 1 along line 2-2', the interfacial dielectric layer **51** may cover the top and side surfaces of the first channel region **21A**. The interfacial dielectric layer **51** may surround the top, bottom and side surfaces of the second channel region **21B**, the third channel region **21C**, and the fourth channel region **21D**. The first gate electrode **55** may surround the top, bottom and side surfaces of the second channel region **21B**, the third channel region **21C**, and the fourth channel region **21D**. The first gate electrode **55** may cover the top and side surfaces of the first channel region **21A**. The first gate dielectric layer **53** may be disposed between the first gate electrode **55** and the interfacial dielectric layer **51**. The interfacial dielectric layer **51** may be omitted.

[0025] Referring to FIG. 5, which illustrates an enlarged portion of FIG. 1 along line 4-4', a pair of second drain regions **48** may be disposed in the second active region **22** at positions adjacent to the second gate electrode **56**. The pair of second drain regions **48** may be spaced apart from each other. The second gate dielectric layer **54** may be disposed between the second gate electrode **56** and the second active region **22**. The lower gate dielectric layer **28** may be disposed between the second gate dielectric layer **54** and the second active region **22**. The second gate spacer **42** may be disposed on the side surface of the second gate electrode **56**. The second gate dielectric layer **54** may extend between the second gate electrode **56** and the second gate spacer **42**.

[0026] The lower gate dielectric layer **28** may have a larger horizontal width than the second gate electrode **56**. The lower gate dielectric layer **28** may protrude, e.g., along the horizontal direction, beyond the second gate electrode **56**. The second gate spacer **42** may be in contact with the top and side surfaces of the lower gate dielectric layer **28**. The second gate spacer **42** may include the second inner spacer **42A** and the second outer spacer **42B**. The second inner spacer **42A** may be in contact with the top and side surfaces of the lower gate dielectric layer **28**. In an exemplary embodiment, the second gate dielectric layer **54** may be disposed on the lower gate dielectric layer **28**.

[0027] Referring again to FIGS. 1 to 5, the first active region **21** and the second active region **22** may be defined on the substrate **20**. The first gate electrode **55** may be disposed across the first active region **21**. The first drain region **47** may be disposed in the first active region **21** at a position adjacent to the first gate electrode **55**. The first undercut region **UC1** may be disposed between the first active region **21** and the first gate electrode **55**. The first gate spacer **41** may be disposed on the side surface of the first gate electrode **55**, and may extend into the first undercut region **UC1**. The first gate spacer **41** may have, e.g., an inverted T shape or an L shape.

[0028] The second gate electrode **56** may be disposed across the second active region **22**. The second drain region **48** may be disposed in the second active region **22** at a position adjacent to the second gate electrode **56**. The lower gate dielectric layer **28** may be disposed between the second active region **22** and the second gate electrode **56**. The second gate spacer **42** may be disposed on the side surface of the second gate electrode **56**. The second gate electrode **56** may be disposed on the top and side surfaces of the second active region **22**. The lower end of the second gate electrode **56** may be disposed at a lower level than the upper end of the second active region **22**. The second gate electrode **56** may have a larger horizontal width than the first gate electrode **55**. In an exemplary embodiment, the lower portion **412** of the first inner spacer **41A** may have substantially the same thickness, e.g., along a vertical direction, as the lower gate dielectric layer **28**.

[0029] FIGS. **6** to **13** are cross-sectional views illustrating semiconductor devices according to exemplary embodiments of the disclosure. FIGS. **6** to **13** are cross-sectional views taken along lines **1-1'**, **2-2'**, **3-3'**, **4-4'** and **5-5'** in FIG. **2**.

[0030] Referring to FIG. **6**, the first active region **21** may include a first notch **21N**, which is disposed adjacent to the top surface of the device isolation layer **25**. The second active region **22** may include a second notch **22N**, which is disposed adjacent to the top surface of the device isolation layer **25**.

[0031] Referring to FIG. **7**, the second active region **22** may include a plurality of semiconductor layers **22A**, **23A**, **22B**, **23B**, **22C**, **23C** and **22D**. The plurality of semiconductor layers **22A**, **23A**, **22B**, **23B**, **22C**, **23C** and **22D** may include a first semiconductor layer **22A**, a second semiconductor layer **23A**, a third semiconductor layer **22B**, a fourth semiconductor layer **23B**, a fifth semiconductor layer **22C**, a sixth semiconductor layer **23C**, and a seventh semiconductor layer **22D**, which are sequentially stacked. The first semiconductor layer **22A** may be defined in the second active region **22**. The first semiconductor layer **22A** may include a semiconductor layer such as a single-crystal silicon layer.

[0032] Each of the second semiconductor layer **23A**, the third semiconductor layer **22B**, the fourth semiconductor layer **23B**, the fifth semiconductor layer **22C**, the sixth semiconductor layer **23C**, and the seventh semiconductor layer **22D** may include a single-crystal semiconductor layer that is formed through an epitaxial growth method. In an exemplary embodiment, each of the third semiconductor layer **22B**, the fifth semiconductor layer **22C**, and the seventh semiconductor layer **22D** may include a single-crystal silicon layer. Each of the second semiconductor layer **23A**, the fourth semiconductor layer **23B**, and the sixth semiconductor layer **23C** may include a single-crystal SiGe layer.

[0033] Referring to FIG. **8**, a plurality of blocking patterns **59** may be disposed between the plurality of first drain regions **47** and the plurality of first gate electrodes **55**. The plurality of blocking patterns **59** may include, e.g., silicon oxide, silicon nitride, silicon oxynitride, or combinations thereof. In an exemplary embodiment, the plurality of blocking patterns **59** may include silicon nitride. The plurality of blocking patterns **59** may be disposed between the plurality of channel regions **21A**, **21B**, **21C** and **21D**. The plurality of blocking patterns **59** may be interposed between the first layer **47A** and the first gate dielectric layer **53**.

[0034] Referring to FIG. **9**, an intermediate gate dielectric layer **128** may be disposed on the lower gate dielectric layer **28**. The second gate dielectric layer **54** may be disposed on the intermediate gate dielectric layer **128**. The intermediate gate dielectric layer **128** may include a material having etch selectivity with respect to the lower gate dielectric layer **28**. The intermediate gate dielectric layer **128** may include a different material from the lower gate dielectric layer **28**. The intermediate gate dielectric layer **128** may have a larger horizontal width than the second gate electrode **56**. The intermediate gate dielectric layer **128** may protrude beyond the second gate electrode **56**. The second inner spacer **42A** may be in contact with the top surface of the intermediate gate dielectric layer **128**.

[0035] Referring to FIG. **10**, the first gate spacer **41** may have various thicknesses and shapes. In an

exemplary embodiment, the portion of the first gate spacer **41** that is located between the first gate electrode **55** and the first active region **21** may be thicker than the lower gate dielectric layer **28**. The outermost portion of the lower gate dielectric layer **28** may be aligned between the second gate spacer **42** and the second gate electrode **56**.

[0036] Referring to FIG. **11**, the portion of the first gate spacer **41** that is located between the first gate electrode **55** and the first active region **21** may have substantially the same thickness as the lower gate dielectric layer **28**. The outermost portion of the lower gate dielectric layer **28** may be aligned between the second gate spacer **42** and the second gate electrode **56**.

[0037] Referring to FIG. **12**, the lower gate dielectric layer **28** may have a smaller horizontal width than the second gate electrode **56**. The second gate spacer **42** may extend in a second undercut region UC2 between the second active region **22** and the second gate electrode **56**. The second gate spacer **42** may have an L shape. In an exemplary embodiment, the second inner spacer **42A** may extend in the second undercut region UC2. The second inner spacer **42A** may have an L shape. The second inner spacer **42A** may be in contact with the side surface of the lower gate dielectric layer **28**.

[0038] Referring to FIG. **13**, the first gate spacer **41** may be disposed on the side surface of the first gate electrode **55**. The first gate dielectric layer **53** may be disposed between the first gate electrode **55** and the first active region **21** and between the first gate electrode **55** and the first gate spacer **41**. The first undercut region (UC1 in FIG. **3**) may be omitted.

[0039] The lower gate dielectric layer **28** may have a smaller horizontal width than the second gate electrode **56**. The second gate spacer **42** may extend in the second undercut region UC2 between the second active region **22** and the second gate electrode **56**. The second gate spacer **42** may have an L shape. The second gate spacer **42** may be in contact with the side surface of the lower gate dielectric layer **28**.

[0040] FIGS. **14** to **27** are cross-sectional views of stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. **14** to **27** are cross-sectional views along lines **1-1'**, **2-2'**, **3-3'**, **4-4'** and **5-5'** in FIG. **2**.

[0041] Referring to FIGS. **2** and **14**, a device isolation layer **25** may be formed on the substrate **20** to define the first active region **21** and the second active region **22**. The first active region **21** may be formed in the first region **11** on the substrate **20**. The second active region **22** may be formed in the second region **12** on the substrate **20**. The first active region **21** may include the plurality of channel regions **21A**, **21B**, **21C** and **21D**. A plurality of sacrificial layers **23** may be formed between the plurality of channel regions **21A**, **21B**, **21C** and **21D**. The plurality of channel regions **21A**, **21B**, **21C** and **21D** and the plurality of sacrificial layers **23** may be stacked alternately and repeatedly. The plurality of channel regions **21A**, **21B**, **21C** and **21D** may include the first channel region **21A**, the second channel region **21B**, the third channel region **21C**, and the fourth channel region **21D**.

[0042] The substrate **20** may include a semiconductor substrate, e.g., a silicon wafer or a silicon-on-insulator (SOI) wafer. Each of the first active region **21** and the second active region **22** may have a height, e.g., along the vertical direction, greater than the horizontal width thereof. Formation of the plurality of channel regions **21A**, **21B**, **21C** and **21D** and the plurality of sacrificial layers **23** may include an epitaxial growth process. In an exemplary embodiment, the plurality of sacrificial layers **23** may include a SiGe layer, formed through an epitaxial growth method. Each of the second channel region **21B**, the third channel region **21C**, and the fourth channel region **21D** may include a Si layer, formed through an epitaxial growth method. The first channel region **21A** may be defined in the substrate **20**. The first channel region **21A** may include a single-crystal Si layer. The second active region **22** may be defined in the substrate **20**. The second active region **22** may include a single-crystal Si layer.

[0043] The device isolation layer **25** may include, e.g., silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, high-k dielectrics, or combinations thereof. The top surface of the

device isolation layer **25** may be formed at a lower level than the top surfaces of the first active region **21** and the second active region **22**. The upper ends of the first active region **21** and the second active region **22** may protrude to a higher level than the top surface of the device isolation layer **25**. The upper corners of the first active region **21** and the second active region **22** may be formed to be rounded.

[0044] Referring to FIGS. **2** and **15**, a buffer layer **27** and the lower gate dielectric layer **28** may be formed on the substrate **20**. In an exemplary embodiment, the buffer layer **27** and the lower gate dielectric layer **28** may be formed simultaneously. The buffer layer **27** and the lower gate dielectric layer **28** may be substantially the same thickness. The buffer layer **27** and the lower gate dielectric layer **28** may include an insulating material, e.g., silicon oxide. The buffer layer **27** may cover the first active region **21**. The lower gate dielectric layer **28** may cover the second active region **22**.

[0045] Referring to FIGS. **2** and **16**, a first mask pattern **29** may be formed to cover the buffer layer **27** and expose the lower gate dielectric layer **28**. Nitrogen may be injected into the lower gate dielectric layer **28**. In an exemplary embodiment, the injecting nitrogen into the lower gate dielectric layer **28** may include a decoupled plasma nitridation (DPN) process, a post-nitridation annealing (PNA) process, or a combination thereof. The first mask pattern **29** may serve to prevent nitrogen from being injected into the buffer layer **27** during the process of injecting nitrogen into the lower gate dielectric layer **28**.

[0046] Referring to FIGS. **2** and **17**, the buffer layer **27** may be exposed by removing the first mask pattern **29**. A plurality of first temporary gate electrodes **31** may be formed across the first active region **21** on the buffer layer **27**. A second mask pattern **33** may be formed on the plurality of first temporary gate electrodes **31**. A plurality of second temporary gate electrodes **32** may be formed across the second active region **22** on the lower gate dielectric layer **28**. A third mask pattern **34** may be formed on the plurality of second temporary gate electrodes **32**.

[0047] In an exemplary embodiment, the plurality of first temporary gate electrodes **31** and the plurality of second temporary gate electrodes **32** may include a polysilicon layer. The second mask pattern **33** and the third mask pattern **34** may include silicon nitride. Formation of the plurality of first temporary gate electrodes **31** and the plurality of second temporary gate electrodes **32** may include an anisotropic etching process using the second mask pattern **33** and the third mask pattern **34** as an etching mask. The buffer layer **27** between the plurality of first temporary gate electrodes **31** may be partially etched, and may be reduced in thickness. The lower gate dielectric layer **28** between the plurality of second temporary gate electrodes **32** may be partially etched, and may be reduced in thickness.

[0048] Referring to FIGS. **2** and **18**, a spacer layer **36L** may be formed on the top and side surfaces of the buffer layer **27**, the lower gate dielectric layer **28**, the plurality of first temporary gate electrodes **31**, the plurality of second temporary gate electrodes **32**, the second mask pattern **33**, and the third mask pattern **34**. A fourth mask pattern **35** may be formed on the spacer layer **36L** to cover the first region **11** and expose the second region **12**.

[0049] A sacrificial spacer **36** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34** by anisotropically etching the spacer layer **36L**. The sacrificial spacer **36** may include silicon nitride. The second active region **22** may be exposed to the outside of the sacrificial spacer **36**. The bottom of the sacrificial spacer **36** may be in contact with the top surface of the lower gate dielectric layer **28**. The sacrificial spacer **36** may be in contact with the side surfaces of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**.

[0050] Referring to FIGS. **2** and **19**, the spacer layer **36L** may be exposed by removing the fourth mask pattern **35**. A fifth mask pattern **38** may be formed to cover the second region **12** and expose the first region **11**. The spacer layer **36L** may be removed.

[0051] Referring to FIGS. **2** and **20**, the fifth mask pattern **38** may be removed.

[0052] Referring to FIGS. **2** and **21**, the first active region **21** may be exposed between the plurality

of first temporary gate electrodes **31** by partially removing the buffer layer **27**. The buffer layer **27** may be preserved between the plurality of first temporary gate electrodes **31** and the first active region **21**. The buffer layer **27** may have a smaller horizontal width than each of the plurality of first temporary gate electrodes **31**. A first undercut region UC1 may be formed under the plurality of first temporary gate electrodes **31**. In an exemplary embodiment, the first undercut region UC1 may be formed between the plurality of first temporary gate electrodes **31** and the first active region **21**.

[0053] The sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34** may be exposed by removing the sacrificial spacer **36**. The lower gate dielectric layer **28** may have a larger horizontal width than a corresponding one of the plurality of second temporary gate electrodes **32**. The lower gate dielectric layer **28** may protrude beyond a corresponding one of the plurality of second temporary gate electrodes **32**.

[0054] Referring to FIGS. **2** and **22**, the first gate spacer **41** may be formed on the sidewalls of the plurality of first temporary gate electrodes **31** and the second mask pattern **33**. The second gate spacer **42** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**. The first gate spacer **41** may include the first inner spacer **41A** and the first outer spacer **41B**. The second gate spacer **42** may include the second inner spacer **42A** and the second outer spacer **42B**. In an exemplary embodiment, the first inner spacer **41A** and the second inner spacer **42A** may include silicon nitride. The first outer spacer **41B** and the second outer spacer **42B** may include silicon oxide or silicon oxynitride.

[0055] The first inner spacer **41A** may be formed on the sidewalls of the plurality of first temporary gate electrodes **31** and the second mask pattern **33**. The first inner spacer **41A** may extend in the first undercut region UC1. The first inner spacer **41A** may be in contact with the bottom surfaces of the plurality of first temporary gate electrodes **31** and with the first active region **21**. The first inner spacer **41A** may be in contact with the side surface of the buffer layer **27**. The first outer spacer **41B** may be formed on the outer side surface of the first inner spacer **41A**.

[0056] The second inner spacer **42A** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**. The second inner spacer **42A** may be in contact with the side and top surfaces of the lower gate dielectric layer **28**. The second outer spacer **42B** may be formed on the outer side surface of the second inner spacer **42A**.

[0057] Referring to FIGS. **2** and **23**, a plurality of first trenches **43** may be formed in the first active region **21** between the plurality of first temporary gate electrodes **31**. A plurality of second trenches **44** may be formed in the second active region **22** between the plurality of second temporary gate electrodes **32**.

[0058] Referring to FIGS. **2** and **24**, a plurality of first drain regions **47** may be formed in the plurality of first trenches **43**, and a plurality of second drain regions **48** may be formed in the plurality of second trenches **44**. Each of the plurality of first drain regions **47** may include a first layer **47A** and a second layer **47B** disposed on the first layer **47A**. Each of the plurality of second drain regions **48** may include a third layer **48A** and a fourth layer **48B** disposed on the third layer **48A**. The upper ends of the plurality of first drain regions **47** may protrude to a higher level than the upper end of the first active region **21**. The upper ends of the plurality of second drain regions **48** may protrude to a higher level than the upper end of the second active region **22**.

[0059] Each of the plurality of first drain regions **47** and the plurality of second drain regions **48** may be formed through a selective epitaxial growth (SEG) method. Each of the plurality of first drain regions **47** and the plurality of second drain regions **48** may include SiGe, Si, SiC, or combinations thereof. In an exemplary embodiment, each of the first layer **47A** and the third layer **48A** may include a Si layer, and each of the second layer **47B** and the fourth layer **48B** may include a SiGe layer. In an exemplary embodiment, the first layer **47A** may include a SiGe layer having a lower Ge density than the second layer **47B**. The third layer **48A** may include a SiGe layer having a lower Ge density than the fourth layer **48B**.

[0060] Referring to FIGS. 2 and 25, an interlayer insulating layer 49 may be formed on the plurality of first drain regions 47 and the plurality of second drain regions 48. The interlayer insulating layer 49 may include, e.g., silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, high-k dielectrics, or combinations thereof. In an exemplary embodiment, the interlayer insulating layer 49 may include silicon oxide.

[0061] The top surfaces of the plurality of first temporary gate electrodes 31 and the plurality of second temporary gate electrodes 32 may be exposed by removing the second mask pattern 33 and the third mask pattern 34 through a planarization process. The planarization process may include a chemical mechanical polishing (CMP) process.

[0062] Referring to FIGS. 2 and 26, a first gate trench 31T may be formed by removing the plurality of first temporary gate electrodes 31 and the buffer layer 27. A second gate trench 32T may be formed by removing the plurality of second temporary gate electrodes 32.

[0063] Referring to FIGS. 2 and 27, a plurality of gap regions 21G may be formed by removing the plurality of sacrificial layers 23. The plurality of gap regions 21G may communicate with the first gate trench 31T. The plurality of first drain regions 47 may be exposed in the plurality of gap regions 21G.

[0064] The first inner spacer 41A may serve to prevent damage to the plurality of first drain regions 47 during the process of removing the plurality of sacrificial layers 23. The second inner spacer 42A and the lower gate dielectric layer 28 may serve to prevent damage to the plurality of second drain regions 48 and the second active region 22 during the process of removing the plurality of sacrificial layers 23.

[0065] Referring again to FIGS. 1 and 2, the first gate dielectric layer 53 may be formed on the inner walls of the first gate trench 31T and the plurality of gap regions 21G. The second gate dielectric layer 54 may be formed on the inner walls of the second gate trench 32T. The first gate electrode 55 may be formed on the first gate dielectric layer 53 to fill the first gate trench 31T. The second gate electrode 56 may be formed on the second gate dielectric layer 54 to fill the second gate trench 32T.

[0066] Each of the first gate dielectric layer 53 and the second gate dielectric layer 54 may include, e.g., silicon oxide, silicon nitride, silicon oxynitride, high-k dielectrics, or combinations thereof. In an exemplary embodiment, each of the first gate dielectric layer 53 and the second gate dielectric layer 54 may include high-k dielectrics, e.g., metal oxide. Each of the first gate electrode 55 and the second gate electrode 56 may include, e.g., metal, metal silicide, metal nitride, metal oxide, polysilicon, conductive carbon, or combinations thereof. In an exemplary embodiment, each of the first gate electrode 55 and the second gate electrode 56 may include, e.g., work function metal.

[0067] FIGS. 28 to 30 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 28 to 30 are cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2. Hereinafter, only the differences will be briefly described.

[0068] Referring to FIGS. 2 and 28, a fifth mask pattern 38 may be formed to cover the second region 12 and expose the first region 11.

[0069] Referring to FIGS. 2 and 29, the first undercut region UC1 may be formed under the plurality of first temporary gate electrodes 31 by partially removing the buffer layer 27.

[0070] Referring to FIGS. 2 and 30, the fifth mask pattern 38 may be removed. Subsequently, semiconductor devices may be formed in a manner similar to that described with reference to FIGS. 22 to 27.

[0071] FIGS. 31 and 32 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 31 and 32 are cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2.

[0072] Referring to FIGS. 2 and 31, a temporary buffer layer 27A and a lower gate dielectric layer 28 may be formed. In an exemplary embodiment, the temporary buffer layer 27A may be formed

through the same process as the lower gate dielectric layer **28** simultaneously therewith, and may include substantially the same material as the lower gate dielectric layer **28**. The temporary buffer layer **27A** and the lower gate dielectric layer **28** may include, e.g., silicon oxynitride or silicon nitride.

[0073] Referring to FIGS. **2** and **32**, a fifth mask pattern **38** may be formed to cover the lower gate dielectric layer **28** and expose the temporary buffer layer **27A**. The buffer layer **27** may be formed by removing nitrogen in the temporary buffer layer **27A** through a surface modification process, e.g., a descum process. The nitrogen concentration in the buffer layer **27** may be lower than that in the lower gate dielectric layer **28**. The buffer layer **27** may have etch selectivity with respect to the lower gate dielectric layer **28**. The buffer layer **27** may have a higher etching rate than the lower gate dielectric layer **28**. The fifth mask pattern **38** may be removed. Subsequently, semiconductor devices may be formed in a manner similar to that described with reference to FIGS. **17** to **29**.

[0074] FIGS. **33** to **37** are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. **33** to **37** are cross-sectional views along lines **1-1'**, **2-2'**, **3-3'**, **4-4'** and **5-5'** in FIG. **2**.

[0075] Referring to FIGS. **2** and **33**, a sacrificial buffer layer **127** may be formed on the buffer layer **27**. An intermediate gate dielectric layer **128** may be formed on the lower gate dielectric layer **28**. The buffer layer **27** may be formed through the same process as the lower gate dielectric layer **28** simultaneously therewith, and may include substantially the same material as the lower gate dielectric layer **28**. The sacrificial buffer layer **127** may be formed through the same process as the intermediate gate dielectric layer **128** simultaneously therewith, and may include substantially the same material as the intermediate gate dielectric layer **128**.

[0076] In an exemplary embodiment, each of the buffer layer **27** and the lower gate dielectric layer **28** may include, e.g., silicon oxide or silicon oxynitride. The sacrificial buffer layer **127** and the intermediate gate dielectric layer **128** may include different materials from the buffer layer **27** and the lower gate dielectric layer **28**. The sacrificial buffer layer **127** and the intermediate gate dielectric layer **128** may include silicon oxynitride or silicon nitride.

[0077] Referring to FIGS. **2** and **34**, a sixth mask pattern **138** may be formed to cover the intermediate gate dielectric layer **128**. The sacrificial buffer layer **127** may be removed through an isotropic etching process to expose the buffer layer **27**. The sixth mask pattern **138** may be removed.

[0078] Referring to FIGS. **2** and **35**, a plurality of first temporary gate electrodes **31**, a plurality of second temporary gate electrodes **32**, a second mask pattern **33**, and a third mask pattern **34** may be formed.

[0079] Referring to FIGS. **2** and **36**, the first active region **21** may be exposed between the plurality of first temporary gate electrodes **31** by partially removing the buffer layer **27**. The buffer layer **27** may be preserved between the plurality of first temporary gate electrodes **31** and the first active region **21**. The buffer layer **27** may have a smaller horizontal width than each of the plurality of first temporary gate electrodes **31**. A first undercut region **UC1** may be formed under the plurality of first temporary gate electrodes **31**. In an exemplary embodiment, the first undercut region **UC1** may be formed between the plurality of first temporary gate electrodes **31** and the first active region **21**. The intermediate gate dielectric layer **128** may serve to prevent etching damage to the lower gate dielectric layer **28** during the process of forming the first undercut region **UC1**.

[0080] Referring to FIGS. **2** and **37**, the first gate spacer **41** may be formed on the sidewalls of the plurality of first temporary gate electrodes **31** and the second mask pattern **33**. The second gate spacer **42** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**. The first gate spacer **41** may include the first inner spacer **41A** and the first outer spacer **41B**. The second gate spacer **42** may include the second inner spacer **42A** and the second outer spacer **42B**.

[0081] The first inner spacer **41A** may extend in the first undercut region **UC1**. The second inner

spacer **42A** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**. The lower end of the second inner spacer **42A** may be in contact with the top surface of the intermediate gate dielectric layer **128**.

[0082] Referring again to FIGS. **2** and **9**, the intermediate gate dielectric layer **128** may be preserved on the lower gate dielectric layer **28**. The second gate dielectric layer **54** may be formed on the intermediate gate dielectric layer **128**. The intermediate gate dielectric layer **128** may have a larger horizontal width than the second gate electrode **56**. The intermediate gate dielectric layer **128** may protrude beyond the second gate electrode **56**.

[0083] FIGS. **38** to **42** are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. **38** to **42** are cross-sectional views along lines **1-1'**, **2-2'**, **3-3'**, **4-4'** and **5-5'** in FIG. **2**.

[0084] Referring to FIGS. **2** and **38**, the temporary buffer layer **27A** and a temporary lower gate dielectric layer **28A** may be formed. The temporary buffer layer **27A** may be thicker than the temporary lower gate dielectric layer **28A**. In an exemplary embodiment, the temporary buffer layer **27A** and the temporary lower gate dielectric layer **28A** may include the same material. The temporary buffer layer **27A** and the temporary lower gate dielectric layer **28A** may include silicon oxide.

[0085] Referring to FIGS. **2** and **39**, the buffer layer **27** and a lower gate dielectric layer **28** may be formed by injecting nitrogen into the temporary buffer layer **27A** and the temporary lower gate dielectric layer **28A**. In an exemplary embodiment, the injecting nitrogen into the temporary buffer layer **27A** and the temporary lower gate dielectric layer **28A** may include a decoupled plasma nitridation (DPN) process, a post-nitridation annealing (PNA) process, or a combination thereof.

[0086] Referring to FIGS. **2** and **40**, a plurality of first temporary gate electrodes **31**, a plurality of second temporary gate electrodes **32**, a second mask pattern **33**, and a third mask pattern **34** may be formed.

[0087] Referring to FIGS. **2** and **41**, the first active region **21** may be exposed between the plurality of first temporary gate electrodes **31** by partially removing the buffer layer **27**. The buffer layer **27** may be preserved between the plurality of first temporary gate electrodes **31** and the first active region **21**. A first undercut region UC1 may be formed under the plurality of first temporary gate electrodes **31**.

[0088] The lower gate dielectric layer **28** may be partially removed during the process of forming the first undercut region UC1. The lower gate dielectric layer **28** may be preserved between the plurality of second temporary gate electrodes **32** and the second active region **22**. Since the lower gate dielectric layer **28** is thinner than the buffer layer **27**, the rate at which the lower gate dielectric layer **28** is etched between the plurality of second temporary gate electrodes **32** and the second active region **22** may be reduced during the process of forming the first undercut region UC1. In an exemplary embodiment, the horizontal width of the lower gate dielectric layer **28** may be substantially the same as that of a neighboring one of the plurality of second temporary gate electrodes **32**, or may be larger than that of a neighboring one of the plurality of second temporary gate electrodes **32**.

[0089] Referring to FIGS. **2** and **42**, the first gate spacer **41** may be formed on the sidewalls of the plurality of first temporary gate electrodes **31** and the second mask pattern **33**. The second gate spacer **42** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**. The first gate spacer **41** may have various thicknesses and shapes. In an exemplary embodiment, the portion of the first gate spacer **41** that is located between the plurality of first temporary gate electrodes **31** and the first active region **21** may be thicker than the lower gate dielectric layer **28**. The outermost portion of the lower gate dielectric layer **28** may be aligned with the side surfaces of the plurality of second temporary gate electrodes **32**. In an exemplary embodiment, the side surface of the lower gate dielectric layer **28** and the side surfaces of the plurality of second temporary gate electrodes **32** may form substantially the same plane.

[0090] Referring again to FIGS. 2 and 10, the portion of the first gate spacer **41** that is located between the first gate electrode **55** and the first active region **21** may be thicker than the lower gate dielectric layer **28**. The outermost portion of the lower gate dielectric layer **28** may be aligned between the second gate spacer **42** and the second gate electrode **56**.

[0091] FIGS. 43 to 46 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 43 to 46 are cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2.

[0092] Referring to FIGS. 2 and 43, the sacrificial buffer layer **127** may be formed on the buffer layer **27**. A lower gate dielectric layer **28** may be formed on the second active region **22**. In an exemplary embodiment, the sacrificial buffer layer **127** may include a material having etch selectivity with respect to the buffer layer **27**. The lower gate dielectric layer **28** may be formed through the same process as the sacrificial buffer layer **127** simultaneously therewith, and may include substantially the same material as the sacrificial buffer layer **127**. The buffer layer **27** may include silicon oxide or silicon oxynitride. The lower gate dielectric layer **28** and the sacrificial buffer layer **127** may include silicon oxynitride or silicon nitride.

[0093] Referring to FIGS. 2 and 44, a plurality of first temporary gate electrodes **31**, a plurality of second temporary gate electrodes **32**, a second mask pattern **33**, and a third mask pattern **34** may be formed.

[0094] Referring to FIGS. 2 and 45, the first active region **21** may be exposed by partially removing the sacrificial buffer layer **127** and the buffer layer **27**. The sacrificial buffer layer **127** may be preserved under the plurality of first temporary gate electrodes **31**. The sacrificial buffer layer **127** may have substantially the same horizontal width as a neighboring one of the plurality of first temporary gate electrodes **31**. A first undercut region UC1 may be formed under the sacrificial buffer layer **127**. The lower gate dielectric layer **28** may be partially removed to expose the second active region **22** during the process of removing the sacrificial buffer layer **127**. The lower gate dielectric layer **28** may have substantially the same horizontal width as a neighboring one of the plurality of second temporary gate electrodes **32**.

[0095] Referring to FIGS. 2 and 46, the first gate spacer **41** may be formed on the sidewalls of the plurality of first temporary gate electrodes **31** and the second mask pattern **33**. The second gate spacer **42** may be formed on the sidewalls of the plurality of second temporary gate electrodes **32** and the third mask pattern **34**.

[0096] Referring again to FIGS. 2 and 11, the outermost portion of the lower gate dielectric layer **28** may be aligned between the second gate spacer **42** and the second gate electrode **56**.

[0097] FIGS. 47 to 51 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 47 to 51 are cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2.

[0098] Referring to FIGS. 2 and 47, the buffer layer **27** and the sacrificial buffer layer **127** may be sequentially stacked on the first region **11** and the second region **12**. The buffer layer **27** and the sacrificial buffer layer **127** may cover the first active region **21** and the second active region **22**. In an exemplary embodiment, the sacrificial buffer layer **127** may include a material having etch selectivity with respect to the buffer layer **27**. The buffer layer **27** may include silicon oxide or silicon oxynitride. The sacrificial buffer layer **127** may include silicon oxynitride or silicon nitride. A first mask pattern **29** may be formed to cover the first region **11** and expose the second region **12**.

[0099] Referring to FIGS. 2 and 48, the buffer layer **27** may be exposed by removing the sacrificial buffer layer **127** in the second region **12**.

[0100] Referring to FIGS. 2 and 49, the sacrificial buffer layer **127** in the first region **11** may be exposed by removing the first mask pattern **29**. The second active region **22** may be exposed by removing the buffer layer **27** in the second region **12**.

[0101] Referring to FIGS. 2 and 50, the buffer layer **27** may be exposed by removing the sacrificial buffer layer **127** in the first region **11**. The buffer layer **27** may cover the first active region **21**.

[0102] Referring to FIGS. 2 and 51, an upper buffer layer 227 may be formed on the buffer layer 27 in the first region 11. A lower gate dielectric layer 28 may be formed on the second active region 22. The lower gate dielectric layer 28 may be formed through the same process as the upper buffer layer 227 simultaneously therewith, and may include substantially the same material as the upper buffer layer 227.

[0103] Subsequently, semiconductor devices may be formed in a manner similar to that described with reference to FIGS. 38 to 46.

[0104] FIGS. 52 to 54 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 52 to 54 are cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2.

[0105] Referring to FIGS. 2 and 52, a buffer layer 27, a lower gate dielectric layer 28, a plurality of first temporary gate electrodes 31, a plurality of second temporary gate electrodes 32, a second mask pattern 33, and a third mask pattern 34 may be formed. The lower gate dielectric layer 28 may be formed through the same process as the buffer layer 27 simultaneously therewith, and may include substantially the same material as the buffer layer 27.

[0106] Referring to FIGS. 2 and 53, the first active region 21 may be exposed between the plurality of first temporary gate electrodes 31 by partially removing the buffer layer 27. The buffer layer 27 may have a smaller horizontal width than each of the plurality of first temporary gate electrodes 31. A first undercut region UC1 may be formed under the plurality of first temporary gate electrodes 31.

[0107] The second active region 22 may be exposed between the plurality of second temporary gate electrodes 32 by partially removing the lower gate dielectric layer 28. The lower gate dielectric layer 28 may be preserved between the plurality of second temporary gate electrodes 32 and the second active region 22. The lower gate dielectric layer 28 may have a smaller horizontal width than each of the plurality of second temporary gate electrodes 32. A second undercut region UC2 may be formed under the plurality of second temporary gate electrodes 32. In an exemplary embodiment, the second undercut region UC2 may be formed between the plurality of second temporary gate electrodes 32 and the second active region 22. Formation of the first undercut region UC1 and formation of the second undercut region UC2 may be performed simultaneously through the same process.

[0108] Referring to FIGS. 2 and 54, the first gate spacer 41 may be formed on the sidewalls of the plurality of first temporary gate electrodes 31 and the second mask pattern 33. The second gate spacer 42 may be formed on the sidewalls of the plurality of second temporary gate electrodes 32 and the third mask pattern 34. The first gate spacer 41 may include the first inner spacer 41A and the first outer spacer 41B. The second gate spacer 42 may include the second inner spacer 42A and the second outer spacer 42B. In an exemplary embodiment, the second gate spacer 42 may have a shape similar to that of the first gate spacer 41.

[0109] The second inner spacer 42A may be formed on the sidewalls of the plurality of second temporary gate electrodes 32 and the third mask pattern 34. The second inner spacer 42A may extend in the second undercut region UC2. The second inner spacer 42A may be in contact with the bottom surfaces of the plurality of second temporary gate electrodes 32 and with the second active region 22. The second inner spacer 42A may be in contact with the side surface of the lower gate dielectric layer 28.

[0110] Referring again to FIGS. 2 and 12, the first gate spacer 41 may extend in the first undercut region UC1 between the first active region 21 and the first gate electrode 55. The lower gate dielectric layer 28 may have a smaller horizontal width than the second gate electrode 56. The second gate spacer 42 may extend in the second undercut region UC2 between the second active region 22 and the second gate electrode 56.

[0111] FIGS. 55 to 57 are cross-sectional views illustrating stages in methods of forming semiconductor devices according to exemplary embodiments of the disclosure. FIGS. 55 to 57 are

cross-sectional views along lines 1-1', 2-2', 3-3', 4-4' and 5-5' in FIG. 2.

[0112] Referring to FIGS. 2 and 55, a buffer layer 27, a lower gate dielectric layer 28, a plurality of first temporary gate electrodes 31, a plurality of second temporary gate electrodes 32, a second mask pattern 33, and a third mask pattern 34 may be formed.

[0113] A first active region 21 may be exposed between the plurality of first temporary gate electrodes 31. The buffer layer 27 may be preserved between the plurality of first temporary gate electrodes 31 and the first active region 21. The buffer layer 27 may have substantially the same horizontal width as a neighboring one of the plurality of first temporary gate electrodes 31. The side surface of the buffer layer 27 and the side surfaces of the plurality of first temporary gate electrodes 31 may form substantially the same plane.

[0114] A second active region 22 may be exposed between the plurality of second temporary gate electrodes 32. The lower gate dielectric layer 28 may be preserved between the plurality of second temporary gate electrodes 32 and the second active region 22. The lower gate dielectric layer 28 may have substantially the same horizontal width as a neighboring one of the plurality of second temporary gate electrodes 32. The side surface of the lower gate dielectric layer 28 and the side surfaces of the plurality of second temporary gate electrodes 32 may form substantially the same plane.

[0115] Referring to FIGS. 2 and 56, the fourth mask pattern 35 may be formed to cover the first region 11. A second undercut region UC2 may be formed under the plurality of second temporary gate electrodes 32 by partially removing the lower gate dielectric layer 28. The lower gate dielectric layer 28 may have a smaller horizontal width than each of the plurality of second temporary gate electrodes 32. In an exemplary embodiment, the second undercut region UC2 may be formed between the plurality of second temporary gate electrodes 32 and the second active region 22.

[0116] Referring to FIGS. 2 and 57, the fourth mask pattern 35 may be removed. A first gate spacer 41 may be formed on the sidewalls of the plurality of first temporary gate electrodes 31 and the second mask pattern 33. A second gate spacer 42 may be formed on the sidewalls of the plurality of second temporary gate electrodes 32 and the third mask pattern 34.

[0117] The first inner spacer 41A may be formed on the sidewalls of the plurality of first temporary gate electrodes 31 and the second mask pattern 33. The first inner spacer 41A may be in contact with the side surface of the buffer layer 27. The first inner spacer 41A may be aligned outside the plurality of first temporary gate electrodes 31. The second inner spacer 42A may be formed on the sidewalls of the plurality of second temporary gate electrodes 32 and the third mask pattern 34. The second inner spacer 42A may extend in the second undercut region UC2. The second inner spacer 42A may be in contact with the bottom surfaces of the plurality of second temporary gate electrodes 32 and with the second active region 22. The second inner spacer 42A may be in contact with the side surface of the lower gate dielectric layer 28.

[0118] Referring again to FIGS. 2 and 13, the first gate spacer 41 may be formed on the side surface of the first gate electrode 55. The first gate dielectric layer 53 may be formed between the first gate electrode 55 and the first active region 21 and between the first gate electrode 55 and the first gate spacer 41. The lower gate dielectric layer 28 may have a smaller horizontal width than the second gate electrode 56. The second gate spacer 42 may extend in the second undercut region UC2 between the second active region 22 and the second gate electrode 56.

[0119] By way of summation and review, optimized shapes of gate spacers and replacement gate electrodes are required. Therefore, exemplary embodiments provide semiconductor devices with optimized gate spacer shapes, thereby improving electrical properties of the semiconductor devices and methods of forming the same.

[0120] That is, according to the exemplary embodiments, a semiconductor device includes a gate spacer on a side surface of a gate electrode, such that the gate spacer extends into an undercut region between the gate electrode and an active region. Due to the gate spacer, defects in the

process of forming the gate electrode may be greatly reduced, and therefore, semiconductor devices having excellent electrical properties may be realized.

[0121] Example embodiments have been disclosed herein, and although specific terms are employed, they are used and are to be interpreted in a generic and descriptive sense only and not for purpose of limitation. In some instances, as would be apparent to one of ordinary skill in the art as of the filing of the present application, features, characteristics, and/or elements described in connection with a particular embodiment may be used singly or in combination with features, characteristics, and/or elements described in connection with other embodiments unless otherwise specifically indicated. Accordingly, it will be understood by those of skill in the art that various changes in form and details may be made without departing from the spirit and scope of the present invention as set forth in the following claims.

Claims

1. A method of forming a semiconductor device, the method comprising: defining a first active region and a second active region on a substrate; forming a buffer layer on the first active region; forming a lower gate dielectric layer on the second active region; forming a first temporary gate electrode on the buffer layer and a second temporary gate electrode on the lower gate dielectric layer; partially removing the buffer layer to form an undercut region between the first active region and the first temporary gate electrode; forming a first gate spacer on a side surface of the first temporary gate electrode and extending in the undercut region and a second gate spacer on a side surface of the second temporary gate electrode; forming a first drain region in the first active region at a position adjacent to the first temporary gate electrode and a second drain region in the second active region at a position adjacent to the second temporary gate electrode; removing the first temporary gate electrode and the buffer layer; forming a first gate electrode in a region from which the first temporary gate electrode and the buffer layer are removed; removing the second temporary gate electrode; and forming a second gate electrode in a region from which the second temporary gate electrode is removed.
2. The method as claimed in claim 1, wherein forming the undercut region further includes, before the partially removing the buffer layer, forming a sacrificial spacer on a side surface of the second temporary gate electrode.
3. The method as claimed in claim 2, wherein the sacrificial spacer is in contact with a top surface of the lower gate dielectric layer and a side surface of the second temporary gate electrode.
4. The method as claimed in claim 1, wherein the first gate spacer includes: an upper portion disposed on a side surface of the first gate electrode; and a lower portion extending from the upper portion into the undercut region.
5. The method as claimed in claim 4, wherein the lower portion extends between the first active region and the first gate electrode.
6. The method as claimed in claim 4, wherein: the first active region includes a plurality of channel regions, each of the plurality of channel regions being in contact with the first drain region, and the first gate electrode surrounding a top surface, a side surface, and a bottom surface of at least one of the plurality of channel regions.
7. The method as claimed in claim 6, further comprising forming a first gate dielectric layer between the first gate electrode and the plurality of channel regions, such that the first gate dielectric layer extends between the first gate electrode and the first gate spacer, and the first gate dielectric layer is in contact with a side surface and a top surface of the lower portion.
8. The method as claimed in claim 1, further comprising forming a second gate dielectric layer between the lower gate dielectric layer and the second gate electrode, such that the second gate dielectric layer extends between the second gate spacer and the second gate electrode.
9. The method as claimed in claim 1, wherein the second gate electrode has a larger horizontal

width than the first gate electrode, and the lower gate dielectric layer has a larger horizontal width than the second gate electrode.

10. The method as claimed in claim 1, wherein the lower gate dielectric layer protrudes beyond the second gate electrode.

11. The method as claimed in claim 1, wherein the second gate spacer is in contact with a top surface and a side surface of the lower gate dielectric layer.

12. The method as claimed in claim 1, wherein the lower gate dielectric layer has a smaller horizontal width than the second gate electrode, and the second gate spacer extends between the second active region and the second gate electrode.

13. A method of forming a semiconductor device, the method comprising: defining a first active region and a second active region on a substrate; forming a buffer layer on the first active region and a lower gate dielectric layer on the second active region; forming a first temporary gate electrode on the buffer layer and a second temporary gate electrode on the lower gate dielectric layer; forming a sacrificial spacer on a side surface of the second temporary gate electrode; partially removing the buffer layer to form an undercut region between the first active region and the first temporary gate electrode; removing the sacrificial spacer; forming a first gate spacer on a side surface of the first temporary gate electrode and a second gate spacer on a side surface of the second temporary gate electrode; removing the first temporary gate electrode and the buffer layer to form a first gate electrode; and removing the second temporary gate electrode to form a second gate electrode.

14. The method as claimed in claim 13, wherein the buffer layer and the lower gate dielectric layer are formed simultaneously.

15. The method as claimed in claim 13, wherein in the forming of the first temporary gate electrode and the second temporary gate electrode, the buffer layer and the lower gate dielectric layer are partially etched and are reduced in thickness outside the first temporary gate electrode and the second temporary gate electrode.

16. The method as claimed in claim 13, wherein a bottom surface of the sacrificial spacer is in contact with a top surface of the lower gate dielectric layer outside the second temporary gate electrode.

17. The method as claimed in claim 13, wherein the lower gate dielectric layer has a larger horizontal width than the second gate electrode.

18. A method of forming a semiconductor device, the method comprising: defining a first active region on a substrate; forming a buffer layer on the first active region; forming a first temporary gate electrode on the buffer layer; partially removing the buffer layer to form an undercut region between the first active region and the first temporary gate electrode; forming a first gate spacer on a side surface of the first temporary gate electrode; forming a first drain region in the first active region at a position adjacent to the first temporary gate electrode; removing the first temporary gate electrode and the buffer layer; and forming a first gate dielectric layer and a first gate electrode in a region from which the first temporary gate electrode and the buffer layer are removed, wherein: the first active region includes a plurality of channel regions, each of the plurality of channel regions being in contact with the first drain region, the first gate electrode surrounds a top surface, a side surface, and a bottom surface of at least one of the plurality of channel regions, wherein the first gate spacer includes: an upper portion disposed on a side surface of the first gate electrode; and a lower portion extending from the upper portion into the undercut region, and wherein the first gate dielectric layer extends between the first gate electrode and the first gate spacer and is in contact with a side surface and a portion of a top surface of the lower portion.

19. The method as claimed in claim 18, wherein the first gate spacer has a shape of L or inverted T.

20. The method as claimed in claim 18, wherein the lower portion extends between the first active region and the first gate electrode.
