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(54) **METHOD FOR MAKING MICROMECHANICAL STRUCTURES HAVING AT LEAST ONE LATERAL, SMALL GAP THEREBETWEEN AND MICROMECHANICAL DEVICE PRODUCED THEREBY**

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(21) Appl. No.: **10/625,992**

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(65) **Prior Publication Data**

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Related U.S. Application Data

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(60) Provisional application No. 60/227,507, filed on Aug. 24, 2000.

(51) **Int. Cl.**[7] **H01L 21/00**

(52) **U.S. Cl.** **438/48**; 438/50

(58) **Field of Search** 438/48–53

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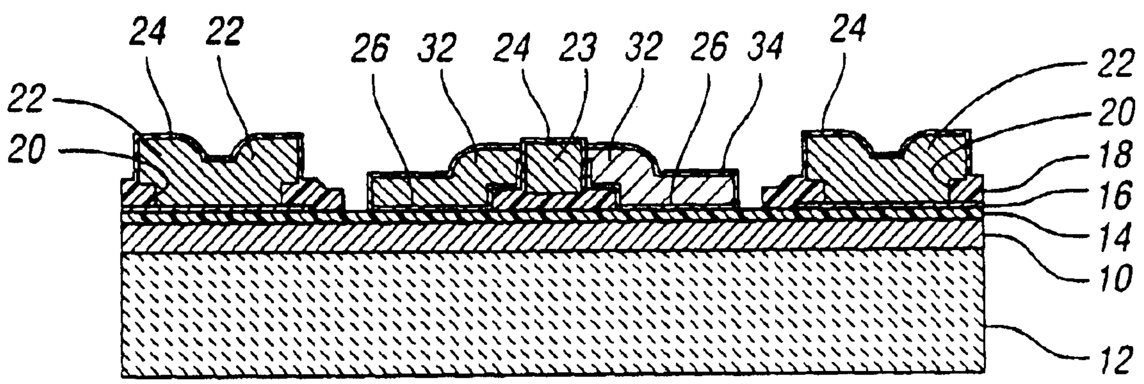
(57) **ABSTRACT**

A method and resulting formed device are disclosed wherein the method combines polysilicon surface-micromachining with metal electroplating technology to achieve a capacitively-driven, lateral micromechanical resonator with submicron electrode-to-resonator capacitor gaps. Briefly, surface-micromachining is used to achieve the structural material for a resonator, while conformal metal-plating is used to implement capacitive transducer electrodes. This technology makes possible a variety of new resonator configurations, including disk resonators and lateral clamped-clamped and free-free flexural resonators, all with significant frequency and Q advantages over vertical resonators. In addition, this technology introduces metal electrodes, which greatly reduces the series resistance in electrode interconnects, thus, minimizing Q-loading effects while increasing the power handling ability of micromechanical resonators.

7 Claims, 2 Drawing Sheets



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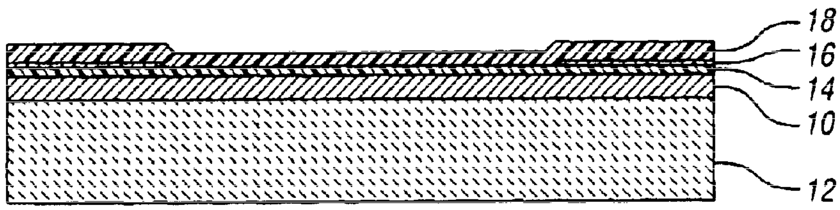

Fig. 1a

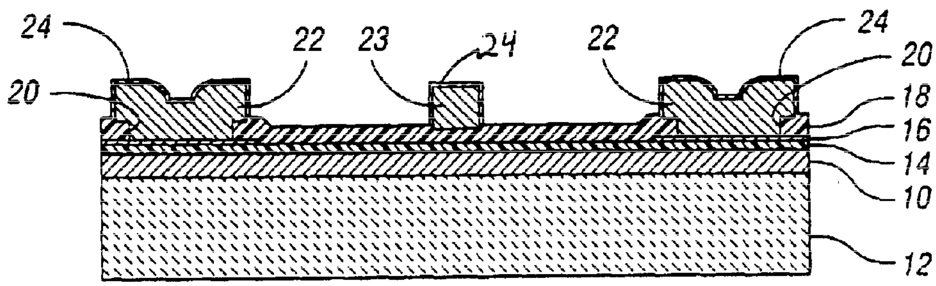

Fig. 1b

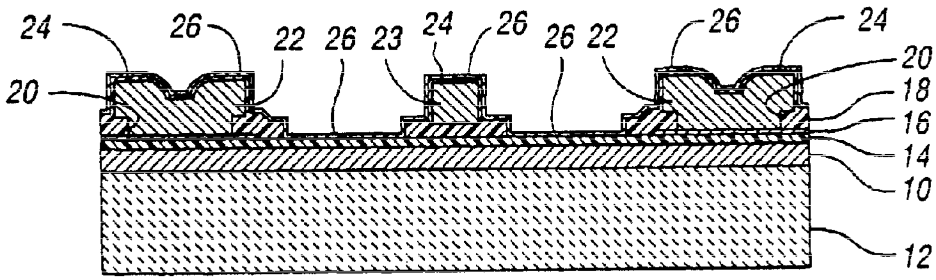

Fig. 1c

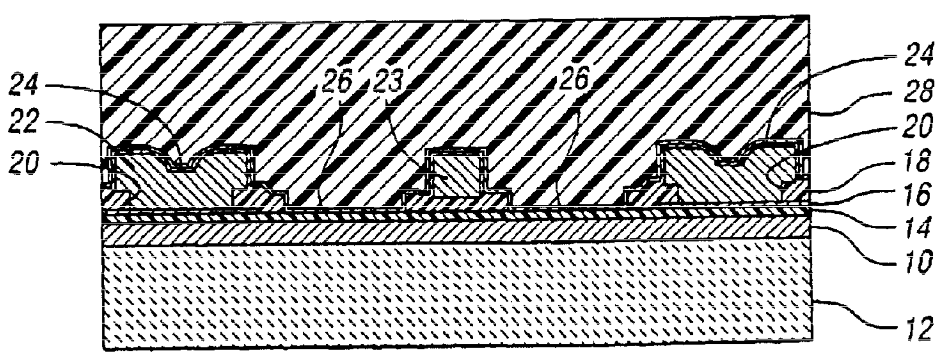

Fig. 1d

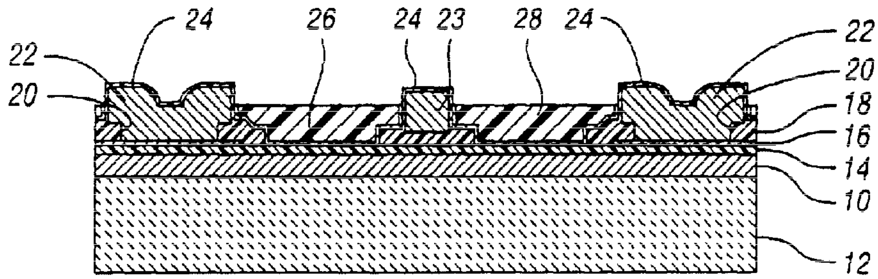

Fig. 1e

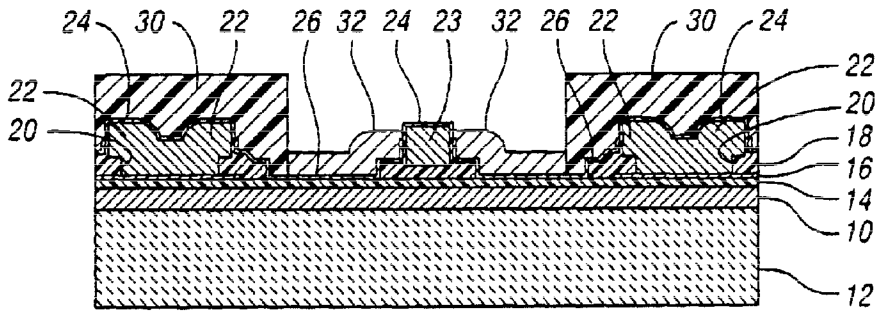

Fig. 1f

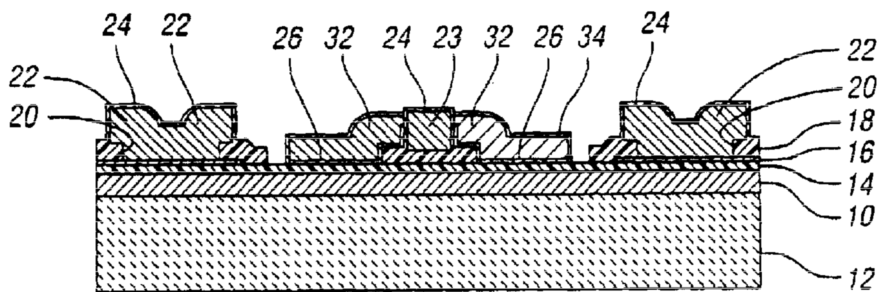

Fig. 1g

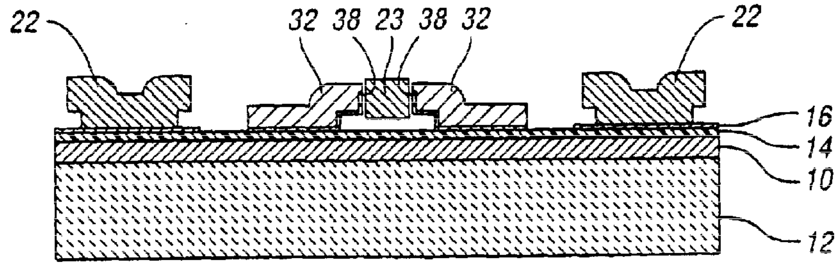

Fig. 1h

METHOD FOR MAKING MICROMECHANICAL STRUCTURES HAVING AT LEAST ONE LATERAL, SMALL GAP THEREBETWEEN AND MICROMECHANICAL DEVICE PRODUCED THEREBY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. Ser. No. 09/938,411 filed Aug. 23, 2003, entitled "Method For Making Micromechanical Structures Having At Least One Lateral, Small Gap Therebetween And Micromechanical Device Produced Thereby" which claims the benefit of U.S. provisional patent application Ser. No. 60/227,507 filed Aug. 24, 2000 and entitled "Process Technology For Lateral Small-Gap Micromechanical Structures".

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under DARPA Contract No. F30602-97-2-0101. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to methods of making micromechanical structures having at least one lateral, small gap therebetween and micromechanical devices produced thereby.

2. Background Art

Vibrating mechanical tank components, such as crystal and SAW resonators, are widely used for frequency selection in communication sub-systems because of their high quality factor (Q's in tens of thousands) and exceptional stability against thermal variations and aging. In particular, the majority of heterodyning communication transceivers rely heavily on the high Q of SAW and bulk acoustic mechanical resonators to achieve adequate frequency selection in RF and IF filtering stages and to realize the required low phase noise and stability in their local oscillators. In addition, discrete inductors and variable capacitors are used to properly tune and couple the front end sense and power amplifiers, and to implement widely tunable voltage-controlled oscillators.

At present, the aforementioned resonators and discrete elements are off-chip components, and must interface with integrated electronics at board level, often consuming a sizable portion of the total sub-system area. In this respect, these devices pose an important bottleneck against the ultimate miniaturization and portability of wireless transceivers. For this reason, many research efforts have been focused on strategies for either miniaturizing these components or eliminating the need for them altogether.

The rapid growth of IC-compatible micromachining technologies that yield micro-scale, high-Q tank components may now bring the first of the above strategies closer to reality. Specifically, the high-Q RF and IF filters, oscillators, and couplers, currently implemented via off-chip resonators and discrete passives may now potentially be realized on the micro-scale using micromachined equivalents based on a variety of novel devices, including high-Q, on-chip, vibrating mechanical resonators, voltage-tunable, on-chip capacitors, isolated, low-loss inductors, microwave/mm-wave medium-Q filters, structures for high frequency isolation packaging, and low-loss mechanical switches. Once these miniaturized filters and oscillators become available, the fundamental bases on which communication systems are developed may also evolve, giving rise to new system architectures with possible power and bandwidth efficiency advantages.

Prototype high-Q oscillators featuring lateral comb-driven micromechanical resonators integrated together with sustaining electronics, all in a single chip, using a planar process that combines surface-micromachining and integrated circuits, have been demonstrated. The gap between the electrodes and the structure of the comb-driven micromechanical resonator is limited by lithography capability. Therefore, a submicron gap is very difficult to do. As the frequency of the resonator goes higher, the size of the resonator becomes smaller. So the electromechanical coupling is smaller. In order to increase the electromechanical coupling, a small-gap between the electrode and the structure is necessary. Although the capacitive gap of vertical micromechanical resonators, which is defined by the thickness of a sacrificial layer, can be very small, clamped-clamped beam vertical micromechanical resonators suffer from lower Q due to anchor dissipation. Also, it normally has only one port which limits its application range. Lateral resonators, on the other hand, have advantages of greater geometric design flexibility and more ports than normally attainable via vertical resonators. However, the electrode-to-resonator gap for capacitively-driven lateral resonators has historically been implemented via lithography and etching, and this greatly limits the degree by which the electrode-to-resonator gap spacing can be reduced.

In order to increase the electromechanical coupling for a lateral micromechanical resonator, a process to form a lateral submicron gap between an electrode and the resonator structure, without the need for advanced lithography tools, is desired.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an improved method of making micromechanical structures having at least one lateral, small gap therebetween and a micromechanical device produced thereby.

In carrying out the above object and other objects of the present invention, a method is provided for making micromechanical structures having at least one lateral gap therebetween. The method includes providing a substrate, and surface micromachining the substrate to form a first micromechanical structure having a first vertical sidewall and a sacrificial spacer layer on the first vertical sidewall. The method also includes forming a second micromechanical structure on the substrate. The second micromechanical structure includes a second vertical sidewall separated from the first vertical sidewall by the spacer layer. The method further includes removing the spacer layer to form a first lateral gap between the first and second micromechanical structures.

The step of surface micromachining may further form a third vertical sidewall on the first micromechanical structure with the sacrificial spacer layer thereon and the method may further include forming a third micromechanical structure including a fourth vertical sidewall separated from the third vertical sidewall by the spacer layer. The step of removing may further form a second lateral gap between the first and third micromechanical structures.

The second micromechanical structure may include an electrode. The first micromechanical structure may include a resonator wherein the first lateral gap is an electrode-to-resonator capacitive gap.

The step of forming may include the step of plating metal on the substrate wherein the second micromechanical structure is a plated metal electrode.

The step of forming may include the step of selective epitaxial growth (SEG) to define the second micromechanical structure.

The method may further include preventing metal from being plated on the first micromechanical structure.

The first lateral gap is preferably a submicron gap.

Further in carrying out the above objects and other objects of the present invention, a micromechanical device is provided. The device includes a substrate, a first micromechanical structure supported on the substrate and having a first vertical sidewall, and a second micromechanical structure supported on the substrate and having a second vertical sidewall. The device further includes a first submicron lateral gap between the first and second vertical sidewalls to increase electromechanical coupling of the first and second micromechanical structures.

The second micromechanical structure may be a plated metal electrode or an SEG grown electrode and the first micromechanical structure may be a lateral resonator.

The first micromechanical structure may have a third vertical sidewall and the device may further include a third micromechanical structure supported on the substrate and having a fourth vertical sidewall and a second submicron lateral gap between the third and fourth vertical sidewalls to increase electromechanical coupling of the first and third micromechanical structures.

The lateral resonator may be a polysilicon resonator such as a flexural-mode resonator beam.

The substrate may be a semiconductor substrate such as a silicon substrate.

The first submicron lateral gap may be a capacitive gap.

The second and third micromechanical structures may be electrodes such as plated metal electrodes.

The first and second submicron lateral gaps may be capacitive gaps.

The above object and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1***a* is a side sectional schematic view of an insulation layer comprising oxide and nitride layers formed on a substrate, a patterned polysilicon layer and a sacrificial oxide layer deposited thereon;

FIG. **1***b* is a side sectional schematic view of the layers of FIG. **1***a* after opening for anchors are formed and a patterned polysilicon layer and a gap sacrificial oxide deposited thereon;

FIG. **1***c* is a side sectional schematic view of the sacrificial oxide after etching and an evaporated seed layer together with the structures of FIG. **1***b;*

FIG. **1***d* is a side sectional schematic view of a thick photoresist for planarization etch back which has been spun on the structures of FIG. **1***c;*

FIG. **1***e* is a side sectional schematic view with the PR etched back to the top of the structures and the seed layer etched on the top of the structures;

FIG. **1***f* is a side sectional schematic view of the structures of FIG. **1***e* after the PR is stripped, a PR plating mold is formed and Au electrodes are plated;

FIG. **1***g* is a side sectional schematic view of the structures of FIG. **1***f* with the PR mold stripped, the seed layers removed and an Ni layer formed on the electrodes; and

FIG. **1***h* is a side sectional schematic view of the structures of FIG. **1***g* after HF release and the Ni layer removed.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A preferred embodiment for a small-gap, lateral resonator process flow of the present invention is presented in FIGS. **1***a*–**1***h*. As shown in FIG. **1***a*, this process starts with a 2 μm thick oxide film **10** (i.e. SiO_2) thermally grown on a silicon substrate **12** and a 3000 Å thick film **14** of nitride (i.e. Si_3N_4) which together serve as an isolation layer. After a 3000 Å thick low stress polysilicon layer **16** is deposited via LPCVD, doped and patterned via reactive ion etching (RIE), a 5000 Å thick layer **18** of sacrificial oxide (i.e. SiO_2) is deposited by LPCVD.

As shown in FIG. **1***b*, vias **20** are patterned into the sacrificial oxide layer **18** by RIE, exposing the underlying polysilicon layer **16** in specific areas to later serve as anchors for eventual structures. A 2 μm thick structural layer of low stress polysilicon is then deposited via LPCVD and patterned also via RIE to form anchor structures **22** and a resonator structure **23** with straight side walls. A 1000 Å thick layer **24** of conformal LPCVD oxide is then deposited in order to define the small-gap spacing of the present invention. This oxide could also be thermally grown over the polysilicon or silicon structures.

As shown in FIG. **1***c*, the sacrificial oxide layer **18** is then etched (RIE and wet etch) until the isolation nitride layer **14** is exposed in regions where metal electrodes are to be formed. A thin metal layer (Cr200 Å/Au300 Å/Cr200 Å) is then evaporated over all areas of the wafer to serve as a seed layer **26** for electrode plating. The top Cr layer of the seed layer **26** is used to enhance the adhesion between the seed layer **26** and a plating mold while the bottom Cr layer of the seed layer **26** is for the adhesion between the middle Au layer and the underneath nitride layer **14**.

As shown in FIG. **1***d*, in order not to plate metal on top of the structures **22** and **23** while forming the electrode, a thick layer **28** of photoresist (PR) is first spun on. Then, the layer **28** is planarized and etched back via RIE to expose the seed metal layer **26** on top of the structures **22** and **23** as shown in FIG. **1***e*. The seed layer **26** on top of the structures **22** and **23** is then removed by wet etching to prevent metal from plating over the tops of the polysilicon structures **22** and **23** during subsequent electroplating steps.

As shown in FIG. **1***f*, after the rest of the PR is removed, a plating PR mold **30** is formed by lithography, the Cr layer on top of the exposed seed layer **26** is removed and then Au electrodes **32** are plated on the exposed Au layer of the seed layer **26** between vertical side walls of the resonator structure **23** and the photoresist mold **30** which together define the electrode plating boundaries.

As shown in FIG. **1***g*, a thin layer **34** of Ni is plated on the electrodes **32** in order to protect the surface of the Au electrode regions while portions of the seed layer **26** are being removed.

FIG. **1***g* shows the PR mold **30** and the portions of the seed layer **26** removed.

As shown in FIG. **1***h*, the layer **34** of Ni is removed and finally, the resonator structure **23**, separated by sub-micron gaps **38** between the two metal electrodes **32**, is free to move after HF release to remove the layer **24** and the layer **18**.

Benefits accruing to the invention are numerous. For example, the main advantages and contributions of this invention are:

(i) metal electrodes: less interconnect resistance, more power handling;

(ii) submicron, sacrificial-film-determined lateral gaps between the resonator and the electrodes;

(iii) higher Q in some resonators, given the anchoring options;

(iv) increase electromechanical couplings, thus increase the efficiency of resonators, gyroscopes, accelerometers, etc.;

(v) allow more flexible mechanical circuit configurations;

(vi) make high frequency disk resonators possible;

(vii) makes stress-compensated resonators possible; and

(viii) makes two-port resonator oscillator configurations easier to manufacture.

The method of the invention can be used to form:

(1) micromechanical structures (including resonators, gyroscopes, and accelerometers, etc.) driven and sensed by metal electrodes plated along the side walls of the structure; and

(2) small capacitive gaps between the micromechanical structure and plated metal electrodes defined by the thickness of sacrificial layer (not only oxide, this sacrificial layer can be any kind of material).

The etch back process used to prevent metal plated on top of the resonator structure **23** (FIGS. **1***d*–**1***e*) is also particularly useful. Also particularly useful is the seed layer combination Cr/Au/Cr or Cr/Ni that survives in straight HF release. Optional plated metals (Au, Ni, Pd, Pt, Cu) also can serve as electrode materials. Alternatively, the process can be modified wherein epi-Si is grown to serve as the electrodes.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.

What is claimed is:

1. A method for making micromechanical structures having at least one lateral gap therebetween, the method comprising:

providing a substrate;

surface micromachining the substrate to form a capacitively-driven, lateral micromechanical structure having a first vertical sidewall and a sacrificial spacer layer on the first vertical sidewall;

forming a first capacitive transducer electrode on the substrate, the first capacitive transducer electrode including a second vertical sidewall separated from the first vertical sidewall by the spacer layer; and

removing the spacer layer to form a first lateral submicron capacitive gap between the micromechanical structure and the first capacitive transducer electrode to increase electromechanical coupling therebetween.

2. The method as claimed in claim **1** wherein the step of surface micromachining further forms a third vertical sidewall on the micromechanical structure with the sacrificial spacer layer thereon and wherein the method further comprises forming a second capacitive transducer electrode including a fourth vertical sidewall separated from the third vertical sidewall by the spacer layer and wherein the step of removing further forms a second lateral submicron gap between the micromechanical structure and the second capacitive transducer electrode.

3. The method as claimed in claim **1** wherein the micromechanical structure includes a resonator and wherein the first lateral submicron capacitive gap is an electrode-to-resonator capacitive gap.

4. The method as claimed in claim **1** wherein the step of forming includes the step of plating metal on the substrate and wherein the first capacitive transducer electrode is a plated metal electrode.

5. The method as claimed in claim **4** further comprising preventing metal from being plated on the micromechanical structure.

6. The method as claimed in claim **1** wherein the step of forming includes the step of growing the first capacitive transducer electrode via selective epitaxial growth.

7. The method as claimed in claim **1** wherein the step of forming includes the steps of depositing polysilicon and etching the polysilicon to form the first capacitive transducer electrode.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,846,691 B2

DATED : January 25, 2005

INVENTOR(S) : Wan-Thai Hsu, John R. Clark and Clark T.-C. Nguyen

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,
Item [63], **Related U.S. Application Data**, "Aug. 23, 2003" should read -- Aug. 23, 2001 --.

Column 1,
Line 11, "Aug. 23, 2003" should read -- Aug. 23, 2001 --.

Signed and Sealed this

Twenty-fourth Day of May, 2005

JON W. DUDAS

Director of the United States Patent and Trademark Office