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(71) Applicant (*for all designated States except US*): **ATMEL CORPORATION** [US/US]; 2325 Orchard Parkway, San Jose, CA 95131 (US).

(72) Inventors: **LOJEK, Bohumil**; 4830 Langdale Way, Colorado Springs, CO 80906 (US). **WHITEMAN, Michael, D.**; 1344 Pinon Ridge Court, Woodland Park, CO 80866 (US).

(74) Agent: **SCHNECK, Thomas**; Schneck & Schneck, P. O. Box 2-E, San Jose, CA 95109-0005 (US).

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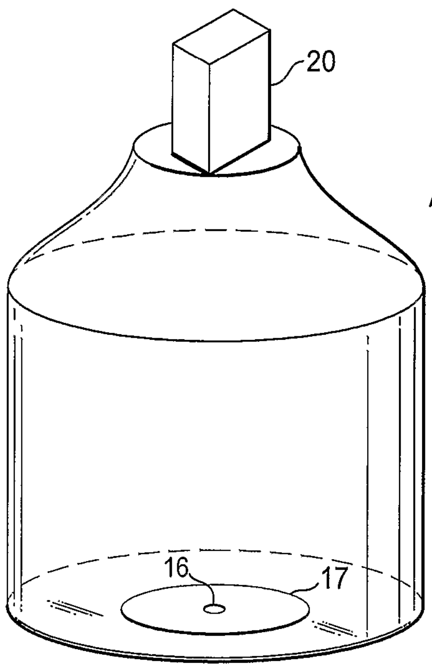
(54) Title: NON-THERMAL ANNEALING OF DOPED SEMICONDUCTOR MATERIAL



(57) Abstract: A method of non-thermal annealing of a silicon wafer comprising irradiating a doped silicon wafer (10, 17) with electromagnetic radiation (14) in a wavelength or frequency range coinciding with lattice phonon absorption resonances of the doped semiconductor material. The wafer is annealed in an apparatus (18) including a cavity and a radiation source (20) of a wavelength ranging from 10-25 µm and more particularly 15-18 µm, or a frequency ranging from 12-30 THz and more particularly 16.5-20 THz.

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Description

NON-THERMAL ANNEALING OF DOPED SEMICONDUCTOR MATERIAL

TECHNICAL FIELD

The invention relates to the annealing of crystalline materials, in general, and to athermal annealing of doped semiconductor materials, in particular.

BACKGROUND OF THE INVENTION

After ion implantation, semiconductor wafers are annealed to remove any damage including near-surface lattice modification caused by the implantation and to activate dopants. Annealing treatments are intended to reduce or eliminate damage to the semiconductor material. For example, annealing occurs when the wafer is exposed to high temperatures ranging from 800°C to 1100°C. Also, short pulses of laser or electron beam radiation can be used to heal damage to semiconductor crystals that occur during the implantation of impurities. However, prior art annealing techniques, especially high temperature annealing, may result in unwanted diffusion of impurities deteriorating quality of the resulting semiconductor device.

Thus, low temperature annealing techniques for promoting healing of damaged semiconductor regions are desired. For example, mechanical energy is used to anneal semiconductor wafers. As described in U.S. Patent No. 6,001,715 to Manka et al., large amplitude sound waves created by laser ablation are used to anneal crystalline materials.

It is an object of the present invention to anneal semiconductors doped by ion-implantation or other doping methods which cause damage to the wafer.

It is an object of the present invention to provide a non-thermal process of annealing a doped semiconductor material.

It is an object of the present invention to provide a process of annealing a semiconductor material implanted with dopants.

It is an object of the present invention to provide a new and improved process of annealing semiconductors.

SUMMARY OF THE INVENTION

These and other objects have been met by a method of non-thermal annealing of a silicon material comprising irradiating a doped silicon material, such as a wafer, with electromagnetic radiation in a wavelength or frequency range coinciding with phonon frequencies in the doped semiconductor material. Although ideal pure crystals have a distinct phonon spectrum with very sharply defined wavelengths (see absorption peaks of Fig. 1) that would need to be matched precisely by an external irradiation source to achieve phonon resonance, real-world silicon wafers used for manufacturing integrated circuits contain impurities, deliberately introduced dopants, and crystal lattice defects that tend to spread out the phonon absorption bands. Therefore, a wavelength in the spread out phonon absorption region of a doped semiconductor material will cause sufficient phonon resonance to produce annealing of the material.

Wavelengths in the phonon absorption region of semiconductor materials having impurities, dopants, and/or crystal lattice defects range from 10-25 μm and more particularly from 15-18 μm (corresponding to a frequency range of 12-30 THz and more particularly from 16.5-20 THz). This wavelength or frequency is in the extreme end of the microwave region and coincides with the phonon absorption region of the spectrum for annealing. Too short a wavelength (or too high a frequency) i.e. less than 10 μm, and the dominant absorption becomes free carrier absorption with significant heating. Likewise, too low a frequency (or too long a wavelength) less than 12 THz, and other heat-inducing absorption mechanisms will be dominant. Note that the invention operates at a frequency far above an ordinary microwave oven of 2.45 GHz frequency and far longer than the visible light or near infrared wavelengths (<1 or 2 μm) of laser thermal annealing or Rapid Thermal Processing (RTP).

For the non-thermal annealing of the present invention, the semiconductor material is placed in an apparatus including a cavity and a radiation source of a particular wavelength. In one embodiment, for maximum annealing effect, the semiconductor material should be positioned so that it coincides with the plane of a standing-wave peak. However, simply placing the wafer in the cavity in any desired position will suffice since the phonon absorption bands are relatively spread out.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is an absorption spectrum of intrinsic silicon in the range of 5 to 35 μm.

Fig. 2 is a simplified diagrammatic view of the annealing process of the present invention.

Fig. 3 is a perspective view of an apparatus for carrying out an annealing of a semiconductor according to the present invention.

Fig. 4 is an absorption spectrum of a typical semiconductor in various absorption ranges including a phonon band absorption range.

BEST MODE FOR CARRYING OUT THE INVENTION

With reference to Fig. 2, the method according to the present invention comprises providing a typical semiconductor material 10, for example silicon or another crystalline material which has a doped region. In addition to purposefully introduced dopants, the material may include other impurities. After having undergone doping by a process (such as ion implantation) which damages the semiconductor material, the material is annealed to repair the damage by exposing the material to electromagnetic radiation in a wavelength or frequency range coinciding with a phonon frequency of the doped semiconductor material. An electromagnetic wave having a frequency coinciding with the phonon frequencies of the doped semiconductor material is indicated by the schematic beam 14 and is incident on the material 10. Reference numeral 12 indicates the position or region of the dopant after ion implantation or other doping process. Upon material exposure to the beam 14 within the frequency or wavelength coinciding with the phonon frequencies of the doped semiconductor material, the semiconductor material 10 is annealed. Enhanced phonon frequency is assumed to be responsible for the annealing mechanism. A specific wavelength range and a specific frequency range used for annealing in the present invention will be discussed below with regard to Fig. 4.

Referring to Fig. 3, in accord with the method of the present invention, the semiconductor material 10, such as a silicon wafer 16, is placed inside a resonator cavity designated 18 coupled by way of a wave guide or traveling wave tube 20 to an electromagnetic generator such as a microwave and/or far infrared generator or free electron laser (not shown). The cavity may comprise for example, a metal material, or may further comprise a liner (not shown) to prevent contamination. The cavity may include a cylindrical shape and is at least large enough to accommodate the semiconductor material 10 to be treated. The material is situated in an area within the cavity. In a preferred embodiment, for maximum annealing effect, the material should be positioned so that it coincides with a particular plane of exciting waves in the cavity. For this purpose, a wafer holder 17 capable of micro-positional adjustments or vibrations might be used. However, placing the material in the cavity 18 in any location where it may be irradiated usually suffices to achieve annealing. To achieve annealing, the generator is used to irradiate the semiconductor material within the cavity 18 with electromagnetic radiation in a wavelength or frequency range coinciding with phonon frequencies of the doped semiconductor material 10 or, more specifically, the doped region 12 of the semiconductor material for a pre-determined period. In one example, the semiconductor material is irradiated for a time period between 1-10 minutes, depending on the power incident on the wafer surface.

A wavelength in the phonon frequency will cause enhancement of phonon resonance to produce annealing of the semiconductor material 10. Fig. 4 indicates the location of the phonon bands in the absorption spectrum. Wavelengths in the phonon frequency region (Reststrahlen region) of the typical semiconductor material which is doped range from 10-25 μm and more particularly from 15-18 μm. Frequencies of phonons of the typical semiconductor material, in particular silicon, range from 12-30 THz and more particularly from 16.5-20 THz. The phonon absorption ranges are spread out as compared to the phonon absorption range of pure silicon as seen in Fig. 1. Therefore, an exact wavelength is not required to resonate phonons. Instead a wavelength within the specified range will suffice. In one example, a 15 THz microwave generator was used.

Still referring to Fig. 4, it is seen that too short a wavelength (or too high a frequency) i.e. less than 10 μm (greater than 30 THz), and the dominant absorption becomes free carrier absorption with significant heating. Other heat-inducing absorption mechanisms may also occur with too short a wavelength. Too long a wavelength (or too low a frequency) i.e. greater than 25 μm (less than 12 THz) and free carrier absorption or other heat-inducing absorption mechanisms will become dominant. The invention does not contemplate use of an ordinary microwave oven of 2.45 GHz frequencies.

In one test example, a silicon wafer having a thickness of 150 mm is implanted with 1.0 X 10^{16} atoms of Arsenic @ 40 keV. After doping, the wafer is placed in the cavity 18 and exposed to electromagnetic radiation in a wavelength or frequency range coinciding with phonon absorption resonances of the doped semiconductor material for a period of 6-10 minutes. The maximum wafer temperature reached because of secondary absorption mechanisms like free carrier absorption is around 400°C - 450°C for irradiation "pulses" on the order of 6-10 minutes. In the example, annealing of a doped layer of the wafer occurs after and during irradiation. In this example, annealing of Arsenic is not a complete annealing, though annealing does occur without excessive exposure to high temperatures.

Claims

1. A method for annealing a doped region of a semiconductor material, the method comprising:

irradiating the semiconductor material with electromagnetic radiation in a wavelength range coinciding with phonon absorption resonances of said doped region of said semiconductor material, thereby annealing said semiconductor material.

2. The method of claim 1 wherein said phonon absorption resonances of said doped region of said semiconductor material occur over a range greater than a range of phonon frequencies of a pure semiconductor material lacking a dopant.

3. The method of claim 1 wherein said electromagnetic radiation is far infrared radiation.

4. The method of claim 1 wherein said electromagnetic radiation is microwave radiation produced by a microwave generator.

5. The method of claim 4 wherein said microwave generator produces said microwave radiation having a frequency ranging from 12-30 THz, and a wavelength ranging from 10-25 μm.

6. The method of claim 1 wherein said electromagnetic radiation has a wavelength ranging from 15-18 μm.

7. The method of claim 1 wherein irradiating said doped region of said semiconductor material, comprises:

directing a beam of said electromagnetic radiation at said doped region of said semiconductor material.

8. The method of claim 1, wherein irradiating said semiconductor material is carried out within a resonator cavity having an electromagnetic radiation source.

9. The method of claim 8 wherein said resonator cavity is metal.

10. The method of claim 9 wherein said resonator cavity includes a liner.

11. The method of claim 8 wherein said resonator has a cylindrical shape.

12. The method of claim 1 wherein said irradiation occurs for a time of 1-10 minutes.

13. The method of claim 12 wherein the period of time for the irradiation depends upon the radiant power incident on the semiconductor material.

14. The method of claim 1 wherein a temperature of said semiconductor material does not exceed a temperature of 450°C at the conclusion of the irradiation.

15. The method of claim 1 wherein said semiconductor material is a wafer.

16. The method of claim 1 further comprising doping said semiconductor material by ion implantation before annealing.

17. The method of claim 1 wherein said doped semiconductor material is silicon.

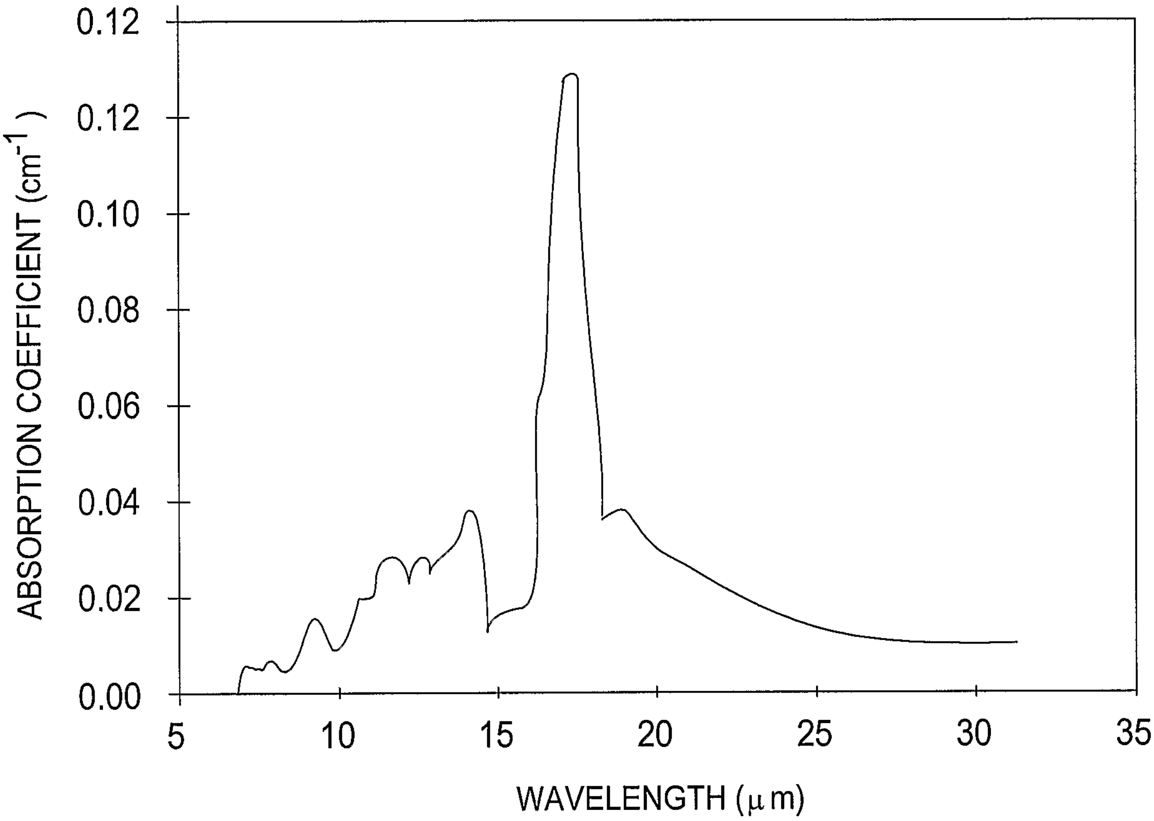

Fig._1 (Prior Art)

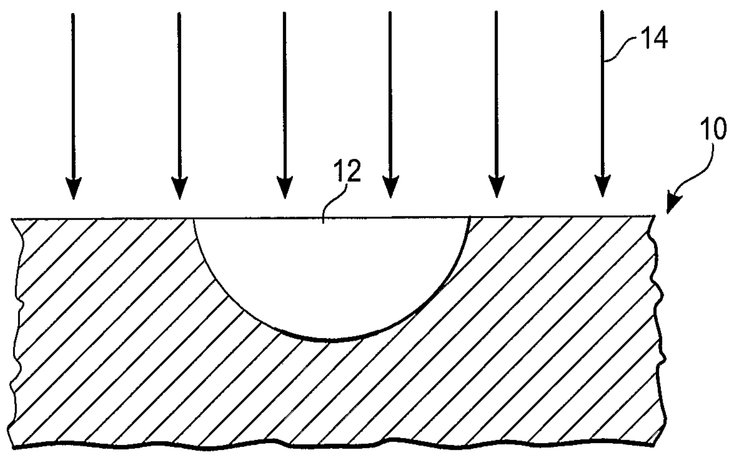

Fig._2

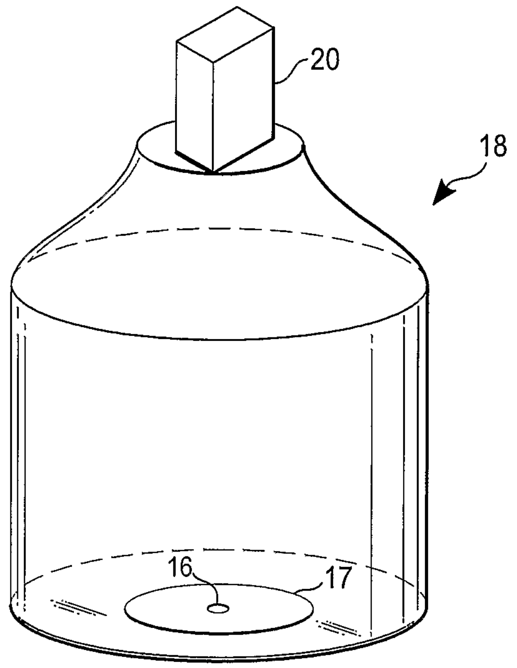

Fig._ 3

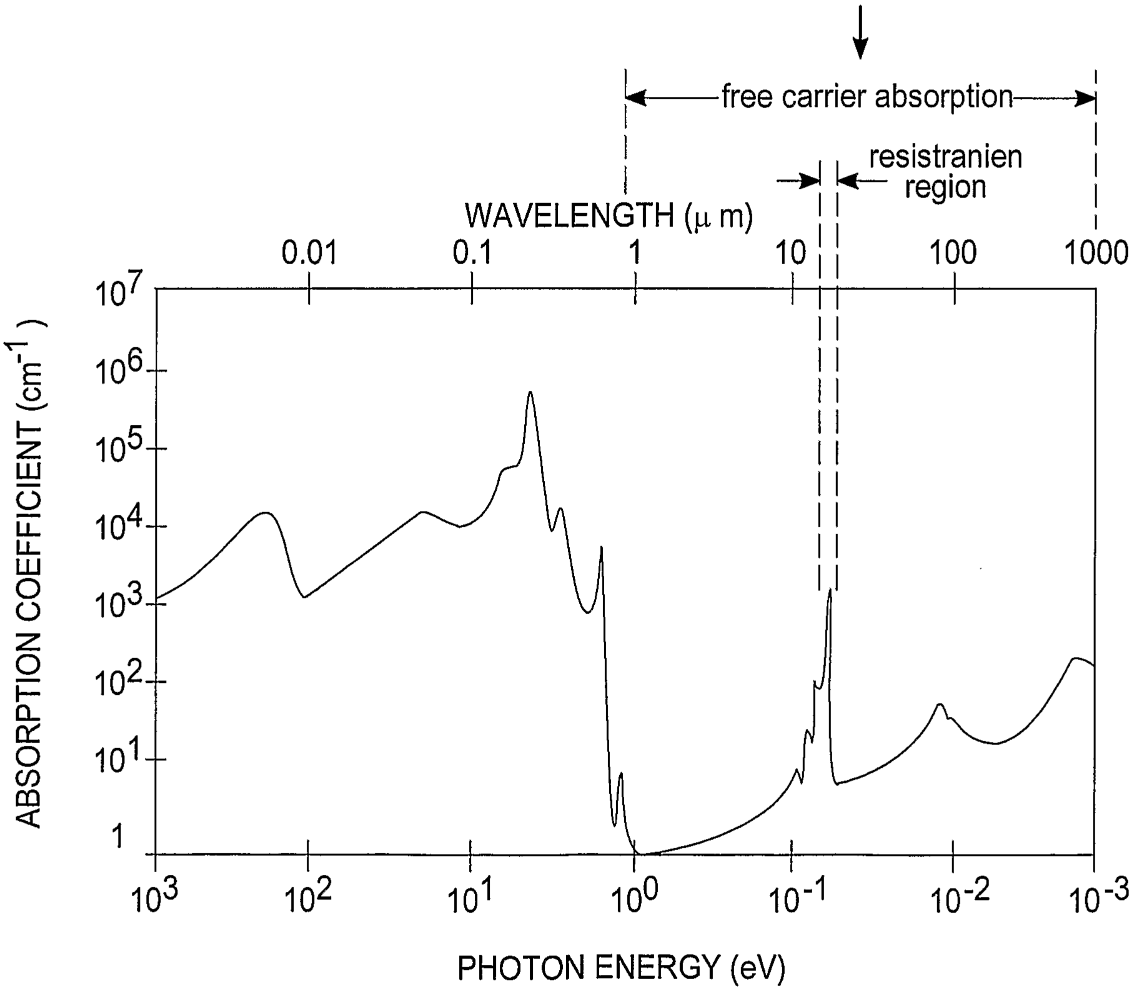

Fig._ 4 (Prior Art)