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(54) Title: AN EXECUTION METHOD OF A DIODE RADIATION SENSOR

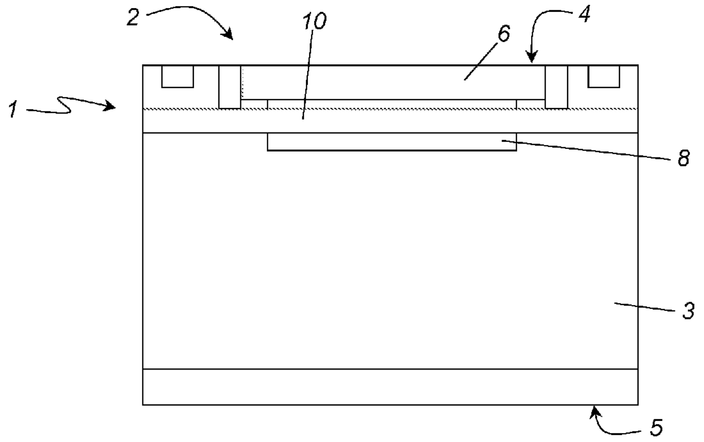

FIG. 1

(57) **Abstract:** An execution method of a diode radiation sensor (1) having charge multiplication diodes (2), the method comprising the following steps: providing a substrate (3) made of semiconductor material, having a front surface (4) and a rear surface (5); making, near the front surface (4), a first layer (6) of semiconductor material doped with a first predetermined amount of a first type of dopant; making, deep in the substrate (3), a second layer (8) of semiconductor material doped with a second predetermined amount of a second type of dopant electrically opposite the first type of dopant. The method comprises, before the steps of making the first layer (6) and the second layer (8), a step of making in the substrate (3) a third layer (10) of semiconductor material enriched with carbon so that it contains a predetermined amount of said carbon.

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AN EXECUTION METHOD OF A DIODE RADIATION SENSOR

DESCRIPTION

Field of application

The present invention can be applied to the field of diode sensors and, in particular, to the field of radiation sensors.

More in detail, the present invention finds particular but not exclusive application to the field of diode radiation sensors having one or more diodes with charge multiplication structure powered so as to work in linear multiplication regime.

Background art

Radiation sensors are used in a wide variety of applications, ranging from industrial to scientific. In many cases, the detector is constructed on a single body of semiconductor material, for example silicon, divided into several microcells or channels (also called pixels and/or microstrips), each typically consisting of an individually accessible diode.

A typical example of an ionizing radiation detector consists of a silicon microstrip with a typical thickness of a few hundred μm. Such a device is used for detecting ionizing radiation (such as charged particles or X-rays) in scientific experiments and for industrial applications.

The active area of the detector is divided into several parallel strips, with a width usually between 25 μm and a few hundred micrometres.

As a first approximation, the above sensors do not have an internal gain and thus have a limit if the amount of charge created by the ionizing radiation is too low to be measured accurately.

To improve performance, it was thus decided to introduce a charge multiplication structure inside the diode which allows them to operate, when appropriately polarized, in linear charge multiplication regime, which means that the charge collected at the output of each channel is proportional to the charge generated by the radiation which interacts with the sensor.

In some cases, such as in the case of measuring the interaction time of charged particles at the minimum ionization in high-energy physics experiments, the charge amplification provided by the diode must be sufficient to allow the detection of the radiation and to obtain an optimal working point considering the ratio between the signal and the noise, but not excessive to avoid impairing the accuracy of the measurement due to the worsening of the signal/noise ratio due to the excess noise determined by the charge multiplication process. For this reason, the diodes used are usually powered so that the gain is particularly limited and with values in the range of 10 to 30. In such a case LGADs are spoken of, i.e., Low-Gain Avalanche Diodes.

Given the type of function which LGADs have and the type of radiation they must measure, the sensors implementing them have active thicknesses which typically range from a few tens to a few hundreds of μm.

One of the most important problems that the aforementioned sensors must face is the fact that their exposure to even intense radiation causes a gradual deterioration thereof.

As is known, in fact, the diode multiplication structures at the base of such sensors are made by appropriately doping a substrate made with a semiconductor (typically, but not exclusively, silicon). The aforesaid radiation can interact with the thus-doped substrate causing the deactivation of the dopant, that is, the removal of the dopant from the crystal lattice, and the return to the original position of semiconductor atoms that the dopant had replaced. In other words, exposure to radiation causes a reduction in the concentration of active dopant in the diodes forming the sensor, decreasing the gain of the junction area of such diodes. This results in a loss of sensor detection accuracy.

In particular, a first drawback is constituted by the fact that the gain of the sensor decreases over time.

A further disadvantage, related in particular to LGAD applications, is constituted by the fact that, since the diode is powered so as to have a limited gain (typically between 10 and 30), the decrease in the doping causes, at the same power supply voltage of the diode, a decrease in the gain.

Presentation of the invention

The object of the present invention is to at least partially overcome the drawbacks noted above, providing an execution method of a diode radiation sensor which allows such sensors to better resist the deteriorating effects of the radiation to which they are exposed.

In particular, an object of the present invention is to provide an execution method of a diode sensor which allows to limit, if not cancel, the deactivation effect of dopant particles in the diodes forming the sensor.

Another object of the present invention is to provide an execution method of a diode sensor having low costs and as comparable as possible to the costs of the known equivalent methods.

It follows that a further object of the present invention is to provide an execution method of a diode sensor which introduces the least possible modifications to the known execution methods currently used for the execution of such sensors.

It is obvious, from what has been said, that another object of the present invention is to provide a diode radiation sensor which is more resistant to the radiation to which it must be subjected in order to limit, if not cancel, the decay of the gain of the diodes forming it.

Such objects, as well as others which will become clearer below, are achieved by an execution method of a diode radiation sensor in accordance with the following claims, which are to be considered as an integral part of the present disclosure.

In particular, the method of the invention allows to make a diode radiation sensor of the type comprising at least one charge multiplication diode.

Firstly, the method comprises a step of preparing a substrate made of semiconductor material. Such a substrate has a front surface and a rear surface opposite the front surface.

At least a first layer of semiconductor material doped with a first predetermined amount of a first type of dopant is then made near the front surface of the substrate.

Subsequently, at least a second layer of semiconductor material doped with a second predetermined amount of a second type of dopant electrically opposite the first type of dopant is then made deep in the substrate.

Obviously, the sequence of doping operations can be any without any limit for the present invention, the formation of the two layers can be reversed. Furthermore, for the creation of electronic components of various types, numerous other steps can be envisaged both before and during the two aforementioned steps as well as interposed therebetween without any limit for the present invention.

According to an aspect of the invention, the method also comprises a step of making a third layer of semiconductor material in the substrate, which is enriched with carbon so that it contains a predetermined amount of such a component.

In other words, the execution of the radiation sensor of the invention occurs as in the prior art, but a step of creating a carbon-enriched layer is added.

In fact, in the presence of radiation, the semiconductor atoms left free from the doping tend to combine with the carbon atoms. In such a case, the same radiation therefore no longer pushes the silicon atoms to return to their original position by kicking the dopant ions which had replaced them during the implantation or diffusion of the same dopant.

Advantageously, therefore, the third carbon-enriched layer allows to reduce, if not cancel, the degradation of the sensor when subjected to radiation.

Since such a result is obtained with a simple carbon enrichment step on a layer of the substrate, it is clear that the execution cost of the radiation sensor of the invention is substantially comparable to the execution cost of the equivalent sensors of the prior art.

According to another aspect of the invention, said step of creating the third carbon-enriched layer occurs before the other layers are made. Typically, but not necessarily, the creation of the third layer occurs with the preparation of the substrate. Advantageously, therefore, the modifications introduced to the normal execution methods of the known sensors are limited only to the aforesaid carbon enrichment made in the substrate before any other treatment, further simplifying the execution of the method of the invention.

Still typically, but not necessarily, the creation of the third layer concerns the entire substrate for its length and for its width. Advantageously, since this third layer is made before any other operation, it does not need to be patterned, thus allowing strong savings both in terms of executive complexity and in economic terms.

From the above, it is evident that said objects are achieved by a diode radiation sensor comprising at least one charge multiplication diode and made according to the teachings of the above method.

Brief description of the drawings

Further features and advantages of the invention will become more evident in light of the detailed description of a preferred but non-exclusive embodiment of an execution method of a radiation sensor according to the invention, illustrated by way of non-limiting example with the aid of the accompanying drawings, in which:

- FIG. 1 depicts a diode radiation sensor made according to the method of the invention;
- the sequence of FIGS. 2 to 3 depicts the result of the execution of some of the steps of the method of the invention.

Detailed description of an exemplary preferred embodiment

With reference to the above mentioned figures, an execution method of a diode radiation sensor **1** **having** one or more charge multiplication diodes **2** is described. According to the embodiment which is described, such charge multiplication diodes **2** are intended to be polarized so as to work in a linear multiplication zone, being LGAD, but such an aspect must not be considered limiting for the invention.

For ease of description, the sensor **1** depicted in the figures comprises a single diode **2**, but it is evident that such an aspect must also not be considered limiting for the present invention.

The method of the invention firstly includes a step of preparing a substrate **3** made of semiconductor material and having two surfaces, a front surface **4** and a rear surface **5** opposite the front surface **4**. Such a substrate **3**, given the use of the embodiment described in the context of the aforementioned LGAD, has a typically high depth and of the order of a few hundred μm or, typically but not necessarily, of at least 20 μm. It is also typically slightly doped, but such an aspect is also not limiting for the present invention.

Always according to the embodiment which is described, the substrate **3** is made of silicon, but also such an aspect must not be considered limiting for the invention.

According to an aspect of the invention, there is then a step of making, near the front surface **4** of the substrate **3**, a first layer **6** of semiconductor material doped with a first predetermined amount of a first type of dopant.

In the embodiment described, the first type of dopant is an N-type dopant obtained by implanting phosphorus in the substrate **3**, but this should not be considered limiting for different embodiments of the invention where the dopant is different (e.g., arsenic) and/or the first type of dopant is a P-type dopant (in which case boron is typically, but not necessarily, used). Also the implantation technique used must not be considered as limiting for different embodiments of the invention where it is carried out by diffusion from the front surface.

Also the position of the first layer **6** near the front surface **4** of the substrate **3** is a feature which should not be considered limiting for the present invention, depth in the substrate, size and number of first layers being able to be any in accordance with the design needs of the radiation sensor.

According to another aspect of the invention, there is also a step of making, deep in the substrate **3**, a second layer **8** of semiconductor material doped with a second predetermined amount of a second type of dopant electrically opposite the first type of dopant.

In accordance with what has been said above for the first layer **6**, in the embodiment which is described, the second type of dopant is a P-type dopant typically executed by implanting boron in the substrate **3**, but also in this case this should not be considered limiting for the present invention with regard to the specific dopant, and for the electrical sign, and for the technique used.

Also the position, size and number of second layers are non-limiting features for the present invention.

As previously mentioned, for the purposes of the present invention the sequence of doping operations can be any, the formation of the two layers can be reversed. Furthermore, for the creation of electronic components of various types, numerous other steps can be envisaged both before and during the two aforementioned steps as well as interposed therebetween without any limit for the present invention.

In the figure it is observed that first layer **6** and second layer **8** are separated, but such a feature should also not be considered limiting for different embodiments of the invention where the two layers are partially superimposed.

In the figure it is noted that the substrate **3** is dedicated to a single electronic component, but this should not be understood in a limiting sense for the invention, the number of electronic components being able to be any by partitioning the substrate in agreement. In the case of the embodiment described, the electronic component is a charge multiplication diode **2** adapted to make the sensor **1** of the invention.

According to another aspect of the invention, the disclosed method further comprises a step of enriching a portion of the substrate **3** with carbon so as to obtain a third layer **10** of semiconductor material thereon.

In the figure it is noted that the third layer **10** intersects the second layer **8** and is separated from the first layer **6**, but this should not be considered limiting for the present invention.

In particular, the third layer **10**, i.e., the carbon-enriched layer, can in general be arranged at any depth in the substrate **3** in accordance with the design parameters. It may therefore, according to embodiments not shown herein, also superimpose the first layer or be separated from both the first and from the second layer.

Its thickness as well as the number of third layers are also non-limiting features for the present invention.

Advantageously, in fact, the carbon tends to combine with the silicon ions released from the substrate lattice during doping, whereby the advantageous effect of making the third layer **10** is avoiding that, following the radiation hitting the diode **2**, the dopant is released to be replaced by the same silicon ions, whatever the dopant itself may be. Since what matters is to obtain such an effect, the depth at which the third layer **10** is made is linked to the mobility of the silicon ions. Such a datum can be predetermined by the technician upon the design, depending, purely by way of example, on the radiation to which the sensor **1** of the invention is intended to be subjected, as well as on design parameters such as the type and quantity of dopants, the thickness and positioning of the first layer **6** and the second layer **8**. Likewise, even the number of third layers and the thickness thereof are clearly deducible at the design step and are not features to be understood as limiting the present invention.

Advantageously, as said, the execution method described so far allows to make a radiation sensor **1** particularly resistant to the deteriorating effects of the radiation to which it is subjected. In fact, as just mentioned, these do not cause the return of silicon ions to the position occupied by the dopant since these ions are already engaged by carbon. Therefore, the gain of the diode **2** will remain unchanged or vary in a quantitatively insignificant manner.

Since the carbon enrichment step is executed on the entire substrate **3**, it does not require the masking arrangement, thereby limiting the execution costs of the sensor **1** according to the method of the invention.

Typically, moreover, the carbon enrichment step for the execution of the third layer is executed during or immediately after the preparation of the substrate **3**, that is, before any other processing step to be carried out on the substrate **3**.

Advantageously, this allows to avoid hindering subsequent implantation or diffusion operations. Thus, the costs of the subsequent execution steps are kept unchanged with respect to the known equivalent methods.

It follows, moreover, that the modification introduced maintains the execution methods of the known electronic components substantially unchanged, substantially consisting in a pre-treatment of the substrate **3** before the execution of one of such methods. In fact, whatever the known method chosen, the method of the invention is characterized by the addition of an initial carbon enrichment step of the substrate **3** at a predetermined depth in the design step of the sensor **1** based on the estimate of the mobility of the silicon ions. The known methods certainly include a multiplicity of other steps which are irrelevant for the purposes of the present patent. The sensor **1** depicted in the same figure 1, as can be seen, comprises further implantations not described herein since, as mentioned, they are irrelevant for the purposes of the present patent.

From what has been said above, it is evident that the object of the present patent is also a radiation sensor **1** obtained with the method described above.

In such a sense, it comprises the charge multiplication diode **2** where the following are identified:

- the substrate **3** made of semiconductor material;
- the third layer **10** of carbon-enriched semiconductor material;
- the first layer **6** of semiconductor material doped with a first type of dopant;
- the second layer **8** of semiconductor material doped with a second type

of dopant electrically opposite the first type of dopant.

In light of the foregoing, it is understood that the execution method of a radiation sensor of the invention achieves all the preset objects.

In particular, it allows to make a diode radiation sensor particularly resistant to the deteriorating effects of the radiation to which the sensor is subjected.

In fact, with the method of the invention, a radiation sensor has been made in which the effect of releasing dopant particles in the diodes forming the sensor is limited, if not cancelled.

On closer inspection, the execution method of the invention has low costs and comparable to the costs of the known equivalent methods since it presents a small but significant variation in the execution process of the sensor consisting of the addition of a step of enriching a layer of the substrate with carbon.

The invention is susceptible to numerous modifications and variations, all falling within the appended claims. Moreover, all the details may furthermore be replaced by other technically equivalent elements, and the materials may be different depending on needs, without departing from the protection scope of the invention defined by the appended claims.

CLAIMS

1. An execution method of a diode radiation sensor (**1**) having at least one charge multiplication diode (**2**), said method comprising the following steps:

- arranging a substrate (**3**) made of semiconductor material, having a front surface (**4**) and a rear surface (**5**) opposite said front surface (**4**);
- making, at least near said front surface (**4**) of said substrate (**3**), at least a first layer (**6**) of semiconductor material doped with a first predetermined amount of a first type of dopant;
- making, deep in said substrate (**3**), at least a second layer (**8**) of semiconductor material doped with a second predetermined amount of a second type of dopant electrically opposite said first type of dopant,

said method being **characterized in that** it comprises, prior to said steps of making said first layer (**6**) and second layer (**8**), a step of making in said substrate (**3**) a third layer (**10**) of semiconductor material enriched with carbon so that it contains a predetermined amount of said carbon.

2. Method according to claim 1, **characterized in that** said step of making said third layer (**10**) is simultaneous with said step of making in said substrate (**3**).

3. Method according to claim 1 or 2, **characterized in that** said third layer (**10**) extends over the entire length of said substrate (**3**).

4. Method according to one or more of the preceding claims, **characterized in that** said third layer (**10**) extends over the entire width of said substrate (**3**).

5. Method according to one or more of the preceding claims, **characterized in that** said first layer (**6**) and said second layer (**8**) are at least partially superimposed.

6. Method according to one or more of the preceding claims, **characterized in that** said first layer (**6**) and said third layer (**10**) are at least partially superimposed.

7. Method according to one or more of the preceding claims, **characterized in that** said second layer (**8**) and said third layer (**10**) are at least partially superimposed.

8. Method according to one or more of the preceding claims,

characterized in that said first type of dopant is an n-type dopant, said second type of dopant being a p-type dopant.

9. Method according to one or more of claims 1 to 7, **characterized in that** said first type of dopant is a p-type dopant, said second type of dopant being an n-type dopant.

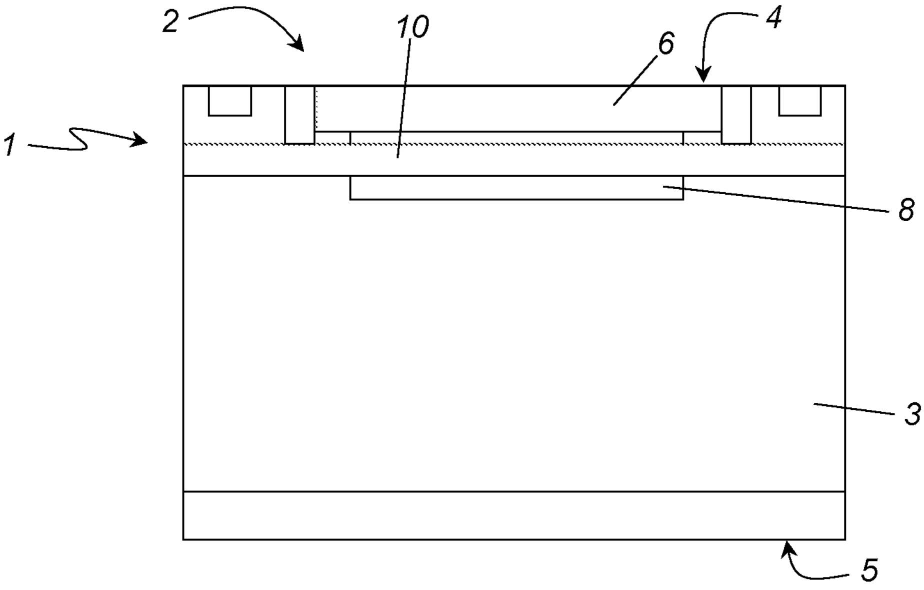

FIG. 1

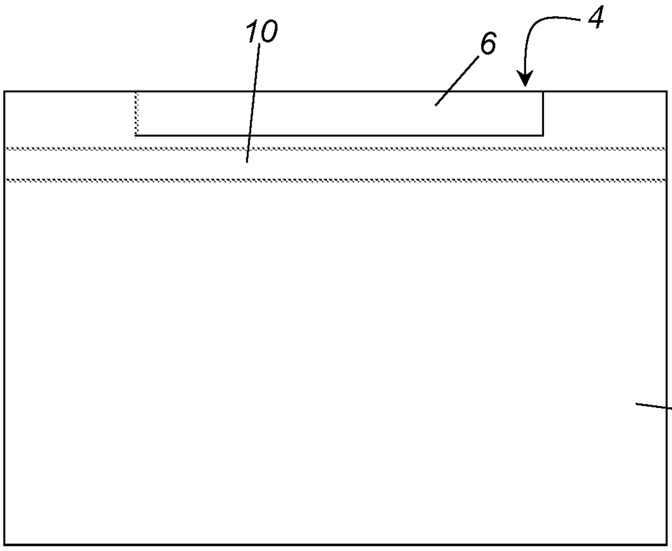

FIG. 2

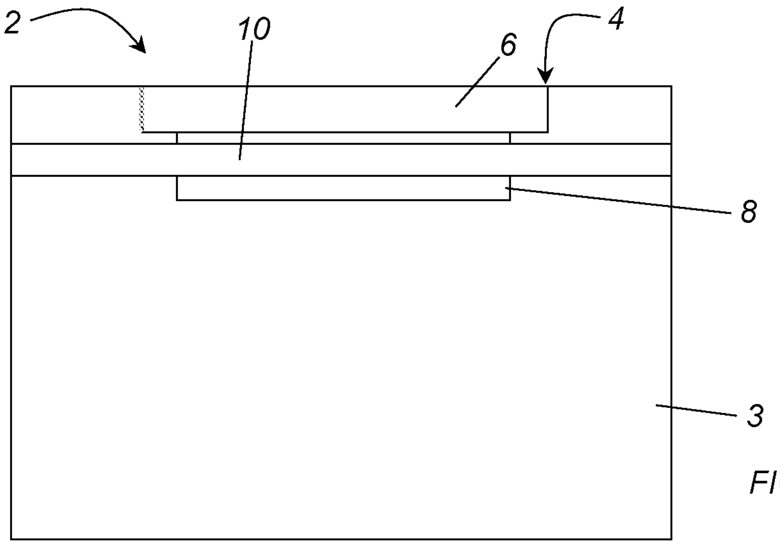

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2023/051597

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L31/18

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SOLA V ET AL: "First FBK Production of 50mum Ultra-Fast Silicon Detectors", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 12 February 2018 (2018-02-12), page 1, XP081420473, DOI: 10.1016/J.NIMA.2018.07.060 abstract page 2, paragraph 4 - page 4, paragraph 1 table 1 ----- -/--	1-9

☒ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search 20 April 2023	Date of mailing of the international search report 02/05/2023
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Ekoué, Adamah

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/051597

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	MENGZHAO LI ET AL: "Effects of shallow carbon and deep N++ layer on the radiation hardness of IHEP-IME LGAD sensors", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 25 October 2021 (2021-10-25), XP091080359, abstract page 1, right-hand column, paragraph 3 - page 2, paragraph 1 table 1 figure 1 -----	1-9
A	Simone ET AL.: "Overview of radiation resistant LGAD designs CPAD workshop (2021, Virtual)", , 18 March 2021 (2021-03-18), pages 1-26, XP055957901, Retrieved from the Internet: URL:https://indico.fnal.gov/event/46746/contributions/210257/attachments/141110/177757/090321_CPAD_LGAD_radhard.pdf [retrieved on 2022-09-05] pages 5,6,8,10 -----	1-9

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