Doping of GaP layers grown by molecular-beam epitaxy on silicon substrates

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Abstract
We investigated the possibility of doping GaP layers with silicon and beryllium to produce contact layers to create light-emitting devices on a silicon substrate. In the process of epitaxial growth, it was possible to solve the problem of the appearance of antiphase regions and germinating dislocations which can capture the carriers. As a result, we obtain GaP layers of n- and p-type with a high degree of doping of good structural quality by molecular-beam epitaxy, suitable for making contacts for LEDs on a Si substrate.

1. Introduction
Nowadays, silicon is the most common semiconductor material in the production of semiconductor electronics. The implementation of light emitting devices based on silicon will dramatically increase the functionality of silicon microelectronics and open up entirely new areas of its application.

Due to the fact that silicon has an indirect structure of electronic zones, the implementation of effective light-emitting sources directly on silicon is extremely difficult task.

This is due to the fact that radiative transitions in direct-band semiconductors are a first-order process and the transition probability is high. In indirect-gap semiconductors, radiative recombination appears as a second-order process, so the probability of radiative transitions is much lower. In addition, in indirect-gap semiconductors, as the degree of excitation increases, the losses associated with absorption of radiation on injected free carriers increase more rapidly than amplification.

Dilute nitrides alloys (III-V-N group material) are of wide interest all over the world. On their basis it is possible to create light-emitting devices on a silicon substrate, since they have a direct structure of the energy bands and they can be lattice-matched with silicon. However, the creation of many widely used electronic devices (diodes, transistors, solar cells, etc.) is impossible without the introduction of doping impurities and the production of layers with specified properties to create a contact layer.

Addition of CBr4, Be or Zn in GaP leads to the appearance of p-GaP, while the addition of S, Te, and Si - to n-GaP. However, doping of III-V layers grown on silicon substrates is a difficult task because of the high concentration of defects in the layer caused by the appearance of antiphase regions and stacking faults [1].

2. Experiment
In this work, doped layers of n-GaP and p-GaP grown by molecular-beam epitaxy (MBE) on silicon substrates were investigated. Epitaxial growth was carried out using the MBE VEECO GEN III. Doping of grown materials is provided by single-zone Si and Be sources with low thermal inertia.

To avoid the problem of the formation of antiphase regions during the growth of III-V compounds on silicon (IV material), vicinal silicon substrates (001) disoriented by 4° in the [110] direction were used. In addition, a special method of growing the initial layer (migration-enhanced epitaxy, MEE) was used [2].

The carrier concentration and mobility in n-GaP/Si p-GaP/Si layers was determined by Hall measurements.

3. Results and discussion
There are some difficulties associated with the growth of initial GaP layer on silicon because of the mismatch between the lattice constants and the different number of valence electrons. In our previous
works [3] it was shown that it is possible to create GaP$_{1-x}$N$_x$ layers on silicon substrates of good structural quality by molecular-beam epitaxy. It was shown [3] that the thickness of the occurrence of defects is 50-100 nm, and the density of dislocation outcrops is $\sim 2 \times 10^8$ cm$^{-2}$, which suggests that the GaP buffer layer is of high structural quality.

However, such a number of dislocations on the heterointerface of the Si substrate and the GaP buffer layer do not make it possible to create contact through the substrate. In addition, during the epitaxial growth, Ga and P materials are diffused into the Si substrate [4].

The solution of the problem is the creation of intra-cavity contacts (figure 1), in which with the special etching and passivation of heterostructure layers, the electrodes to the doped p- and n-type layers are provided from above through the active layers.

![Figure 1. Schematic representation of the intra-cavity contacts to the Si/GaP/GaP(As)N LED heterostructure](image)

Thus, the problem arises of creating heavily doped GaP layers of both p-type and n-type. Using of bulk doping of GaP by Si did not allow obtaining a high concentration of carriers in the layer. This is due to the peculiarities of the effusion source of silicon and, as a consequence, to the low flux of silicon during the growth of the heterostructure. Therefore, it was decided to use a delta-doping (figure 2).

![Figure 2. Schematic representation of the doping layers a) GaP:Be and b) GaP:Si](image)

The samples were consisted of an initial layer, grown by the MEE (45 periods) and a doped GaP layer. Doping with beryllium was carried out evenly over the entire thickness of the layer. A periodic structure (20 periods) consisting of a silicon layer ($\delta$Si) and 100 Å GaP:Si was used to obtain the heavily doped GaP:Si layer. The growth rate was 1 Å/s, the total thickness of GaP layers was 0.8 μm. The concentration and mobility of charge carriers at room temperature were determined (table 1).
Table 1. The concentration and mobility of charge carriers at room temperature.

| Sample          | Concentration (cm$^{-2}$) | Mobility cm$^2$/V·s |
|-----------------|---------------------------|---------------------|
| GaP:Be          | $1,0 \cdot 10^{20}$       | 7                   |
| GaP:Si          | $6,0 \cdot 10^{18}$       | 13                  |
| pure GaP (holes) [5] | -                          | $\leq 150$          |
| pure GaP (electrons) [5] | -                          | $\leq 250$          |

The concentration of free charge carriers in the material can decrease due to the large number of defects in the material. However, in our case it was possible to achieve high values (carrier concentration), which indicates a good structural quality of the grown layer.

For comparison, table 1 shows the mobility of electrons and holes in undoped GaP. It is seen that the carrier mobility in a pure material is very small, but in the obtained GaP:Si and GaP:Be layers it decreases approximately 20 times. This is due, first of all, to a high degree of doping, as well as to a fairly low mobility of carriers in pure material. In addition, carrier mobility is reduced due to scattering by roughness and defects that are present at the Si/GaP heterointerface. It should be noted that for the creation of light-emitting devices, the mobility of charge carriers in contact layers is not a key parameter.

4. Conclusion

We investigated the possibility of doping GaP layers with silicon and beryllium to produce contact layers to create light-emitting devices on a silicon substrate. In the process of epitaxial growth, it was possible to solve the problem of the appearance of antiphase regions and germinating dislocations which can capture the carriers. As a result, we obtain GaP layers of n- and p-type with a high degree of doping of good structural quality by molecular-beam epitaxy, suitable for making contacts for LEDs on a Si substrate.

Acknowledgments

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