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High-mobility inverted selectively doped heterojunctions

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We have used reflection high-energy electron diffraction (RHEED) to study the surface recovery of AlGaAs under different conditions. A modified process for growth interruptions was then introduced, where a GaAs monolayer was grown at each growth stop, and the arsenic flux was turned off during the low-temperature phase of growth interruptions. Selectively doped inverted heterojunctions were grown using the modified growth interruptions together with low-growth temperature (to avoid Si and impurity segregation). This combined process gave reproducible electron mobilities as high as 460 000 cm^2/V s with sheet carrier concentration of 2×10^{11} cm^{-2} at 4.2 K.

Much attention has been focused on investigating the differences between normal and inverted selectively doped GaAs–GaAlAs heterojunctions. In the normal structures the doped AlGaAs layer is grown on top of the undoped GaAs layer, and thus the two-dimensional electron gas (2-DEG) is formed at the top edge of the undoped GaAs layer. In the inverted structures the undoped GaAs layer is grown on top of the AlGaAs layer, so that the 2-DEG is formed in the GaAs right on top of the AlGaAs layer.

The inferior low-temperature electron mobilities of inverted structures, always below 100 000 cm^2/V s[1,2] (compared with values as high as 5×10^6 cm^2/V s[3] for the normal structures), were attributed to result from two main problems: dopant (usually Si) and impurity segregation from the AlGaAs into the GaAs–AlGaAs interface, and the GaAs–AlGaAs interface roughness. However, the inverted structures have advantages for some applications due to the easier formation of Ohmic contacts and the better electrical isolation of the 2-DEG from the substrate. The growth of high-quality inverted interfaces is especially important for achieving good quality quantum well and superlattice structures (as they are comprised of an equal number of normal and inverted interfaces).

Past attempts to solve this problem did not lead to reproducible results and were only marginally successful. Si segregation was reduced by using low-growth temperatures,[4,5] which in turn dictated the use of low-growth rates in order to maintain a good crystalline quality. An attempt to improve the interface smoothness was done by reducing the Al mole fraction.[5] The best reported mobilities for the inverted structure were achieved by introducing a short superlattice in the AlGaAs below the 2-DEG, which was believed to reduce impurity movement and improve the surface smoothness.[6] However, these results were never further confirmed.

The important role of including short superlattices and performing growth interruptions in obtaining high-quality epitaxial layers and smooth interfaces by molecular-beam epitaxy (MBE) has already been recognized.[7,8] It has been related both to surface smoothing processes[9] facilitated by the surface migration of the atoms and to impurities gettering at the interfaces.[10]

We have first tackled the problem of improving the quality of inverted heterojunctions by applying growth interruptions in order to improve the quality of the AlGaAs layers. Using reflection high-energy electron diffraction (RHEED) intensity measurements we have optimized the conditions for periodic interruptions during the growth of AlGaAs layers. We thus combined periodic growth interruptions with low-growth temperature in the doped AlGaAs region (to avoid Si segregation) to give, for the first time, a reproducible procedure for growing high-mobility selectively doped single inverted heterojunctions. Electron mobilities as high as 460 000 cm^2/V s were measured at 4.2 K with electron concentration of 2×10^{11} cm^{-2}.

The layers were grown in RIBER 1000-1 system under arsenic stabilized conditions. The intensity of the specular reflection in the RHEED pattern of a (100)-$c(2\times 4)$ As-stable reconstructed surface, with the beam in the (110) azimuth was monitored as a function of time at different roughening and recovery conditions. The intensity of the RHEED pattern was recorded in the conventional way using an optical fiber and an amplifying system.[9]

The RHEED intensity time evolution clearly shows that the smoothness recovery of GaAs layers is much faster and more complete than the recovery of AlGaAs surfaces. Moreover, a similar enhanced recovery can be seen when only 1 or

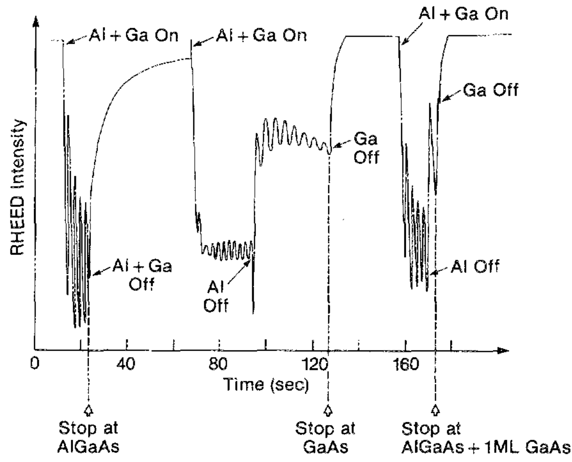

FIG. 1. A typical time evolution of RHEED specular beam intensity taken from (001)-2×4 reconstructed surface, during the growth and recovery of: (a) an AlGaAs layer (left-hand side), (b) 10 ML of AlGaAs covered by 8 ML of GaAs (center), and (c) a few AlGaAs monolayers covered by 1 ML of GaAs (right-hand side).

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2 monolayers (ML) of GaAs are grown on top of an AlGaAs layer. A comparison between surface recoveries at various conditions is given in Fig. 1 for layers grown at 600 °C. The recovery of an $Al_{0.21}Ga_{0.79}As$ surface is seen at the left end of the figure. The following RHEED intensity oscillations reflect the growth of 10 AlGaAs ML followed by 8 GaAs ML. The GaAs surface recovery is considerably faster and more complete (the intensity goes out of scale). We concluded that even a deposition of a single GaAs monolayer on the AlGaAs surface is sufficient for enhancing the recovery process; as can be seen on the right-hand side of Fig. 1. The RHEED intensity recovery is as fast and complete as in the case of the thicker deposition of GaAs on top of AlGaAs.

The arsenic flux is normally left on during growth interruptions, while the substrate temperature is near the congruent sublimation temperature (~600 °C) or above it, in order to prevent the decomposition of the surface. However, we found that at substrate temperatures as low as 500 °C arsenic molecules impinging on the surface during growth stops lead to a roughening of the surface. Figure 2 shows the RHEED intensity from a GaAs surface maintained at 520 °C. The RHEED intensity decreased during growth interruption as long as the arsenic flux was impinging on the surface. As soon as the impinging arsenic flux was turned off the RHEED intensity increased significantly, reflecting the enhanced surface recovery.

Selectively doped inverted heterojunctions investigated in this work were basically conventional (in doping, mole fraction, and growth temperature) structures with a single 2-DEG located in the GaAs on top of the doped AlGaAs layer. A schematic description of the layers configuration is given in Fig. 3. A 0.5-μm-thick buffer layer was first grown at a growth rate of 0.7 μm/h at a substrate temperature of 600 °C. The growth rate was then reduced to 0.20 μm/h, in order to maintain a high-crystalline quality during the subsequent lower temperature growth of 500 °C using during the growth of the Si doped 10-nm-thick $Al_{0.21}Ga_{0.79}As$ layer. Two undoped $Al_{0.21}Ga_{0.79}As$ spacers were grown, the top one ranged from 4–25 nm and the bottom was 100 nm. The bottom spacer prevented a 2-DEG from forming at the bottom (normal) interface. Periodic growth interruptions (including a GaAs recovery monolayer) were introduced during the growth of the AlGaAs layers, according to the procedure described above. A 120-nm-undoped GaAs layer followed the top AlGaAs spacer, capped by 30-nm-thick Si doped GaAs that was designed to be fully depleted by the surface potential.

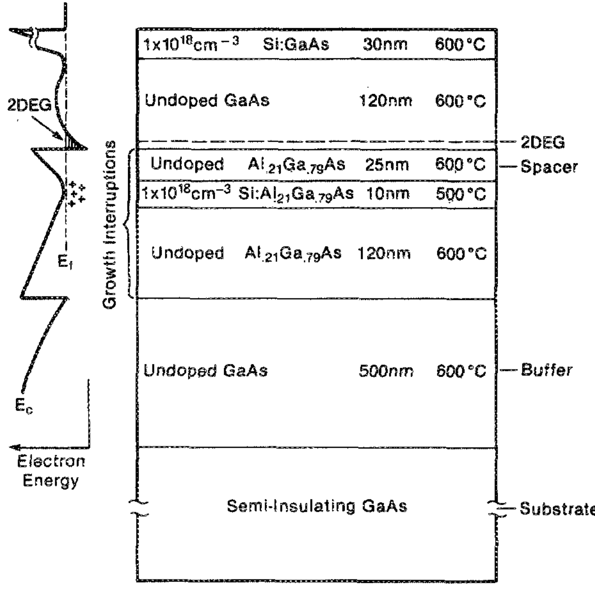

FIG. 3. A schematic cross-sectional view of a typical inverted selectively doped heterostructure, emphasizing the layers in which 20 s long growth interruptions were introduced. A schematic presentation of the respective conduction band diagram is given on the left-hand side of the figure.

Special care was taken to use more frequent growth interruptions at the top 5 nm of the AlGaAs spacer layer. There, we have used a growth stop every 5 ML of AlGaAs. Figure 4 shows the RHEED intensity oscillations recorded during

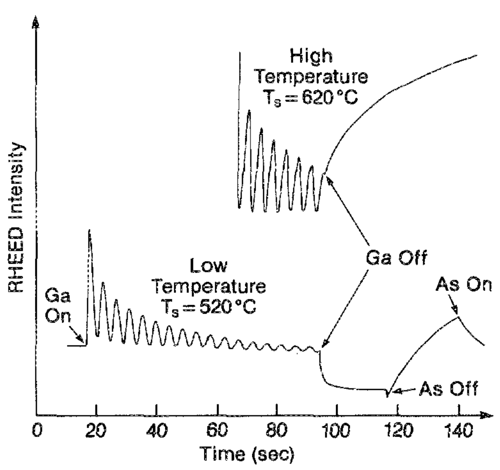

FIG. 2. A typical time evolution of RHEED specular beam intensity taken from (001)-2×4 reconstruction surface, during the growth and recovery of GaAs at 520 °C (bottom) and at 620 °C (top).

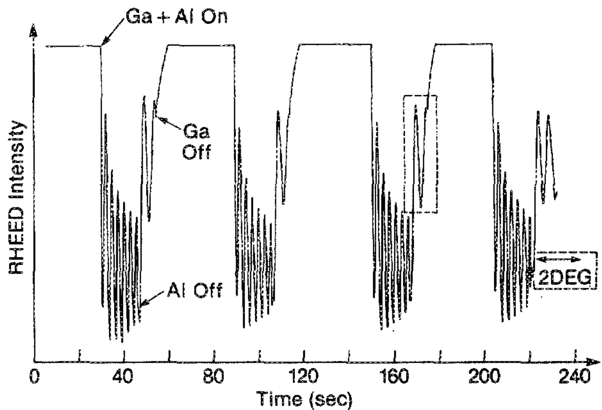

FIG. 4. The RHEED intensity time dependence taken during the growth of the top portion of the AlGaAs spacer layer. The GaAs stop layer can be clearly seen, after each interruption. One of the GaAs stop layers is indicated by a broken line, as well as the point at which the growth of the undoped GaAs layer begins (where the 2-DEG resides).

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TABLE I. The mobilities and carrier concentrations of selectively doped inverted structures, measured at 300, 77, and 4.2 K.

	Spacer	300 K		77 K		4.2 K	
		μ cm^2/V s	n_s cm^{-2}	μ cm^2/V s	n_s cm^{-2}	μ cm^2/V s	n_s cm^{-2}
With many growth stops	25 nm	5000	7.5×10^{11}	130 000	2.5×10^{11}	460 000	2×10^{11}
With one growth stop	24 nm	5000	8×10^{11}	90 000	3×10^{11}	200 000	2.5×10^{11}
No growth stops	20 nm	6000	8×10^{11}	75 000	3.7×10^{11}	150 000	3.6×10^{11}

the growth of the top portion of the AlGaAs spacer. The GaAs recovery layer is clearly seen at each stop, as well as the point at which the growth of the undoped GaAs top layer was initiated. Note that no growth stop was introduced at the very top interface of the AlGaAs layer due to the fear of impurities incorporation at this critical growth interface.

Mobilities and sheet electron concentrations of some structures grown under different conditions that were measured at 300, 77, and 4.2 K in the dark are detailed in Table I. Mobilities as high as 460 000 cm^2/V s with a sheet carrier concentration of 2×10^{11} cm^{-2} were measured at 4.2 K in structures which were grown with many growth interruptions. A lower but still comparatively high 4.2 K mobility of 200 000 cm^2/V s are achieved for the growth in which only a single 1 min long, growth stop was introduced, some 3 nm below the AlGaAs–GaAs interface with no GaAs stop layer. These results are compared with the values achieved when no growth stops were used but the growth temperature was reduced during the growth of the Si-doped AlGaAs layer, to prevent the Si segregation and possible impurities migration. The electron mobility in this case was 150 000 cm^2/V s at 4.2 K for a spacer thickness of 20 nm. We grew some structures with a 4-nm-thick AlGaAs top spacer, using one growth stop 30 nm below the AlGaAs–GaAs interface. The 77 K electron mobility in this case was 70 000 cm^2/V s with a sheet carrier concentration of 8×10^{11} cm^{-2}.

We found that low-temperature growth was needed in order to prevent Si segregation or impurities propagation to the top interfaces. The latter was further demonstrated by growing "normally-off" structures. In these structures, grown on conductive substrates, AlGaAs is undoped and the 2-DEG is accumulated by the application of a positive voltage on the substrate with respect to the top contacts. In these structures, even though Si was not present, it was still essential to reduce the growth temperature within the later part of the AlGaAs layer growth, in order to achieve a high mobility. This clearly indicates that unintentional impurities are present and migrate at higher temperatures towards the top interface. Resuts on the normally-off inverted devices will be published elsewhere.[11]

We relate the enhanced surface recovery of the GaAs covered AlGaAs surfaces to the higher surface diffusion of Ga atoms on GaAs compared with Al and Ga atoms on AlGaAs. The activation energies, for diffusion E_D, were found to be 1.3 and 1.6 eV for Ga on GaAs and Al on AlGaAs, respectively.[12] As a result, the average terrace width on AlGaAs is significantly smaller than on GaAs, reflecting the faster recovery of a GaAs surface. Furthermore, shutting down the arsenic flux during the low temperature (500 °C) growth stops reduces the relative amount of GaAs molecules on the surface which in turn enables the Ga atoms to diffuse much faster.[13] Another mechanism which could be responsible for the improvement in the electron mobilities could be the trapping of impurities at each of the interfaces formed during the growth interruptions layers.[10]

In conclusion, we present for the first time, a reproducible procedure for growing high-mobility selectively doped inverted heterojunctions. The key features are the low-growth temperature to avoid Si and impurities segregation, the slow growth rate and the introduction of modified periodic growth interruptions during the growth of the AlGaAs layers. Mobilities as high as 460 000 cm^2/V s and sheet carrier concentration of 2×10^{11} cm^{-2} were measured at 4.2 K in the dark.

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[1] H. Morkoç, T. J. Durmmond, R. E. Thorne, and W. Kopp, Jpn. J. Appl. Phys. 20, L913 (1981).
[2] S. Sasa, J. Saito, S. Nanbu, T. Ishikawa, and S. Hiyamizu, Jpn. J. Appl. Phys. 23, L573 (1984).
[3] J. H. English, A. C. Gossard, H. L. Störmer, and K. W. Balkwin, Appl. Phys. Lett. 50, 1826 (1987).
[4] K. Inoue and H. Sakaki, Jpn. J. Appl. Phys. 23, L61 (1984).
[5] M. Heiblum, J. Vac. Sci. Technol. B 3, 820 (1985).
[6] T. J. Drummond, J. Klem, D. Arnold, R. Fisher, R. E. Thorne, W. G. Lyons, and H. Morkoç, Appl. Phys. Lett. 42, 615 (1983).
[7] H. Sakaki, M. Tanaka, and J. Yoshino, Jpn. J. Appl. Phys. 24, L417 (1985).

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[8]S. Clarke and D. D. Vvedensky, Appl. Phys. Lett. **51**, 340 (1987).
[9]J. M. Van Hove, C. S. Lent, P. R. Pukite, and P. I. Cohen, J. Vac. Sci. Technol. B **1**, 741 (1983).
[10]P. M. Petroff, R. C. Miller, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 217 (1984).
[11]U. Meirav, M. Heiblum, and F. Stern, Appl. Phys. Lett. (in press).
[12]B. A. Joyce, in Proceedings of the 2nd International Conference on Modulated Semiconductor Structures, Kyoto (1985), p. 1.
[13]Y. Horikoshi, M. Kawashima, and H. Yamaguchi, Jpn. J. Appl. Phys. **25**, L868 (1986).

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