Strategies for achieving high Curie Temperatures in (Ga,Mn)As

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The III$_2$V semiconductor Ga$_{1-x}$Mn$_x$As is one of the most widely studied diluted magnetic semiconductor systems exhibiting carrier mediated ferromagnetism. In this system the ferromagnetism is mediated by the kinetic exchange interaction between the substitutional Mn d$^5$ local moments and the itinerant p-$d$ hybridised holes occupying states near the top of the valence band [1]. Theory predicts that $T_C$ is proportional to the magnetic moment density which depends upon the density of substitutional Mn ions, $x_S$[2,3]. This trend has been confirmed experimentally for samples with $x_S$$<$$6.8\%$ grown by molecular beam epitaxy (MBE) with $T_C$ reaching the previous record of 173K[2]. $x_S$$\approx$$6.8\%$ is achieved for total Mn concentration $x_{\text{total}}$$\approx$$9\%$ with the additional $\approx$$2.2\%$ incorporated as interstitial Mn (Mn$_i$) which can be removed by post-growth annealing[4]. Incorporating higher concentrations of Mn poses challenges because it requires MBE growth to be carried out at relatively low temperatures with the increasing probability of forming defects such as As antisites. We have investigated the growth of Ga$_{1-x}$Mn$_x$As with total Mn concentration as high as $x_{\text{total}}$$=12\%$. We have investigated the effects of growth temperature, As pressure and position on the wafer and found systematic variations allowing the optimisation of these parameters to achieve the highest Curie temperature (Tc). The effect of annealing samples fully at different temperatures indicates that, in addition to removing Mn$_i$, there is another process which is detrimental to ferromagnetism. Annealing at lower temperatures suppresses this second process and has allowed us to achieve a record Tc of 185K[5]. Our studies confirm that $T_C$ continues to increase as the Mn concentration is increased.


**Figure**  Curie temperature after fully annealing at different temperatures for a Ga$_{1-x}$Mn$_x$As wafer with $x_{\text{total}}$$=12\%$. Samples were taken a distance (A) 2.5mm, (B) 7.5mm, (C) 12.5mm and (D) 17.5mm from the centre of the wafer. Inset: $T_C$ for a sample from series B annealed at 170°C for 116 hrs then at 220°C for (1) 1 hour, (2) 2 hour and (3) 2 hour intervals, then at 180°C for 48 hours.