QCSE and Carrier Blocking in P-modulation Doped InAs/InGaAs Quantum Dots

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Abstract: The quantum confined Stark effect in InAs/InGaAs QDs using an undoped and p-modulation doped active region was investigated. Doping potentially offers more than a $3x$ increase in figure of merit modulator performance up to $100\,^{\circ}C$.

1. Introduction

Quantum dot (QD) devices have gathered interest for many reasons, like having the potential to be grown over silicon with little degradation in device performance [1]. InAs/In(Ga)As quantum dot (QD) devices have received a lot of attention in recent years due to their potential to bring efficient lasers to the silicon photonics platform. However other optoelectrionic devices required for optoelectronic integration such as the QD modulator have not heavily studied [1]. The need for high performance, low power modulator devices can be realised through the use of the quantum confined Stark effect (QCSE) and has been demonstrated in both QDs and quantum wells (QW) [2, 3]. The influence of doping in QWs has been studied in [4]. It was shown that the incorporation of a modulation-doped superlattice in a multi-QW structure can lead to equivalent contrast ratios with a $1.8x$ reduction in applied voltage. To the best of our knowledge, there has been no direct comparison between the QCSE in equivalent doped and undoped QD active region stacks. Given the different nature of the states present in QDs, it is expected that modulation doping may lead to even further enhancements to electro-absorption modulator (EAM) performance [1]. QDs also offer the promising prospect of greater temperature tolerance [5], and so here we present a comparison of two identical QD active region stacks, except where p-modulation doping is present in one. We measure the QCSE in both stacks with temperature to determine their potential performance as EAMs, and we show that the inclusion of the p-modulation doping in the stack offers up to $3x$ larger figure of merit (FoM).

2. Results

The segmented contact method was utilized to measure the QCSE in the QD active regions [6]. The active regions used are similar to those we have already measured in [5]. The only difference in the current stack is that the doped stack has a doping concentration in the QD active region of 10 holes per dot.

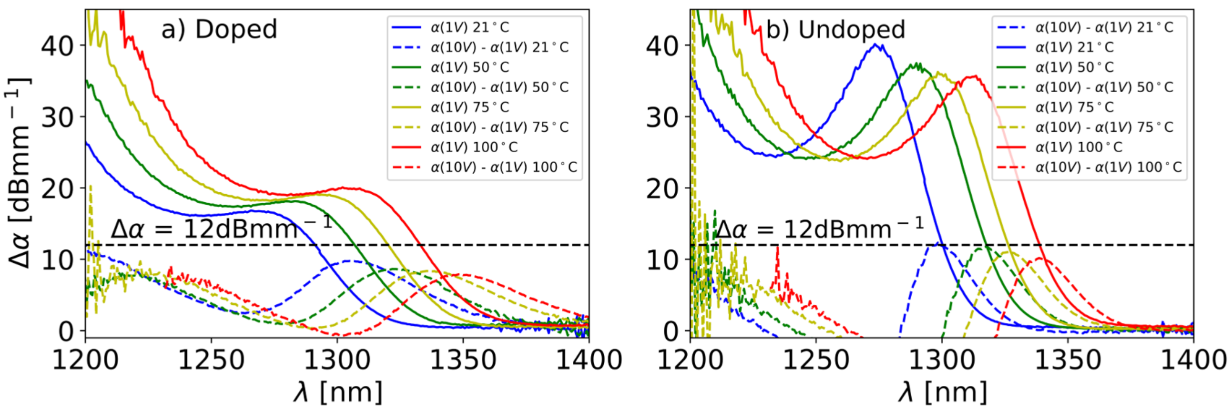

Fig. 1: $\Delta\alpha$ and $\alpha(1V)$ for p-modulated doped (a) and undoped (b) multi-section devices vs temperature.

The measurements are plotted in Fig. 1 and showcase the absorption at a reverse bias of $1V$ $\alpha(1V)$ and change in absorption $\Delta\alpha$ for both the doped and undoped active regions as a function of temperature. It can be seen when comparing the two sets of $\alpha(1V)$ data that unlike the undoped active region, the doped active region's peak absorption strength increases slightly with increasing temperature. This behavior is attributed to the redistribution of carriers in the valence states at elevated temperatures making lower energy transitions more prominent, thus leading to an increase in ground state transition strength. When comparing the $\Delta\alpha$ of both the doped and undoped materials, there is a slight decrease in peak $\Delta\alpha$ with temperature from both active regions, with the undoped sample generally having the larger peak $\Delta\alpha$ value of around $12\,dBmm^{-1}$. Despite the larger $\Delta\alpha$ in the undoped active region, it is important to compare this with the $\alpha(1V)$ to take into account the insertion loss. Hence, we have used the ratio of the $\Delta\alpha$ to the $\alpha(1V)$ as a FoM to compare the two active regions stacks. The FoM for both active regions using a $4V$ and $9V$-swings are presented in Fig. 2. They present a clear indication of the enhancement in active region performance of the doped material. It can be seen in Fig. 2 even up to $100\,°C$ that the doped sample has almost a $3x$ enhancement in the FoM over the undoped sample for both voltage swings. The maximum FoM of the undoped stack is around 2.4 in Fig. 2b for a $9V$-swing. A very similar FoM can be achieved with a $4V$-swing in the doped material as shown in Fig. 2a. The maximum FoM is 8 for the doped stack and degrades with temperature to a value of 5 at $100\,°C$. Nevertheless, the doped active region still works at high temperature and out performs the undoped stack by at least $2x$ over the whole temperature range. This improvement in FoM is mainly attributed to state-filling effects that are present in the doped

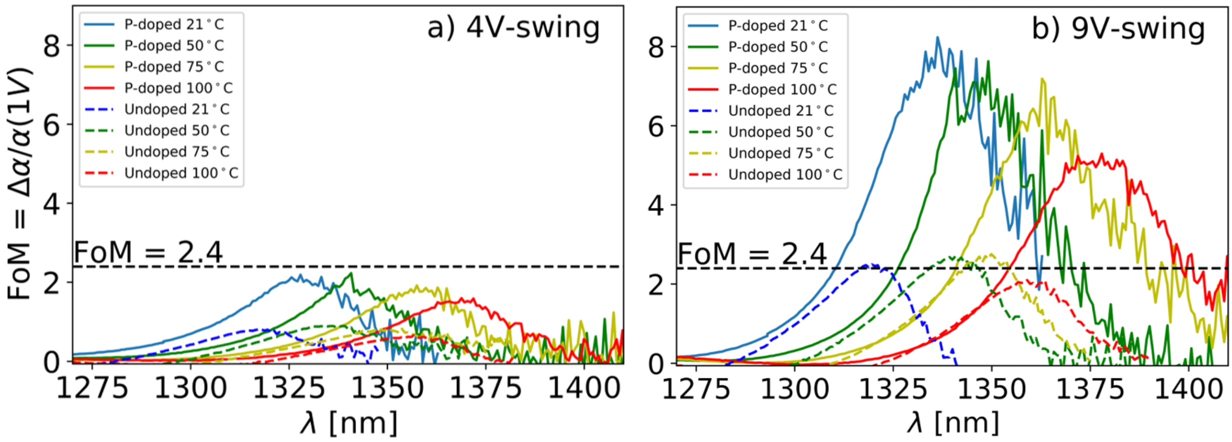

Fig. 2: FoM for a $9V$-swing (a) and $4V$-swing (b) for both doped and undoped QDs vs temperature.

sample. Under the equivalent reverse bias, the doped sample exhibits an enhanced red shift. This red shift with voltage has two contributions, the first being from the Stark shift, with the second originating from the removal of holes from the lowest valence states of the dots. When the doped active region has no external bias applied, the valence states are filled with holes, thus suppressing absorption at the lowest energy dot states and skewing the observed absorption spectrum to high energy. When a reverse bias is applied across the active region, the holes start to be depleted, thus leading to more absorption at lower energy. The reason for this is that the transitions from lower energy states are now becoming possible. This reduction in the carrier blocking effect is different to the reduction in excitonic screening that occurs in QWs [7], and as we have demonstrated more useful for modulators. The carrier depletion also leads to an increase in absorption peak for ground state transitions in the doped stack while in the undoped one, the absorption peak decreases as expected from the QCSE. This effect is also a contributing factor to the improvement in FoM in the doped stack.

3. Conclusion

We have demonstrated the benefit of p-modulation doping in QD active regions by measuring the QCSE up to $100\,°C$. These results demonstrate that p-modulation doping in QDs offer up to $3x$ improvement in the FoM. This will lead better optimised modulators that have an improved trade-off between the extinction ratio and insertion loss and can potentially operate up to $100\,°C$.

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