Optimisation of InGaAs MQW modulator structures operating with 5V or less modulation.

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Abstract
Optimum structures for an InGaAs MQW *pin* diode modulator operating at low voltage (<=5V) are explored where the criterion is maximum reflectivity change.

Keywords: Optical modulators, Fabry-Perot, MQW, InGaAs.

1. Introduction
InGaAs MQW *pin* reflection modulator structures grown on GaAs substrates have the advantage that the substrate is transparent at the operating region. This allows device arrays to be readily flip-chip bonded onto silicon control circuit chips. In this paper we consider the devices operating in digital differential pairs, with voltages being supplied by underlying silicon electronics. Using current best technology this means bias and modulation voltages are limited to 5V, with the trend being to ever lower voltages. In differential mode the important criterion for operation is the difference in reflectivity of the devices, not contrast. The speed of the devices is determined by capacitance, and thus dependent on thickness. This also applies to the use of these devices as detectors in a subsequent array, where the absorption of the device is also a factor. Previous optimisation efforts have been based on a multiplicative combination of some or all of these terms, giving each aspect equal weighting.[1] In this paper we would like to concentrate on maximising the change in reflectivity by the use of a resonant optical cavity, given 5V or less operation, using thin film transfer matrix modelling. The introduction of an optical cavity places greater restrictions on the growth tolerances, which are examined in detail for the case of 5V modulation, and found not to be insurmountable. We subsequently show that the resulting structures are compatible with speed and detector operation requirements. Operation at still lower voltages is summarised.

2. Simple Double-Pass modulator
In order to establish a baseline for comparison we must first establish the best reflectivity change that can be obtained using the absorption change with no optical cavity. In the context of a flip-chip geometry this means a simple double pass modulator with a gold back mirror. The starting data are absorption spectra with different applied electric fields. The samples used (B492 & B499) consisted of a 95 period, 1.4 μm thick strain balanced MQW structure (88Å In(.22)Ga(.78)As, 55Å Al(.15)Ga(.85)As) grown on grading and strain relaxation layers.[2] The structure is outlined in figure 1. The absorption spectrum per quantum well at a given field is extracted and used in transfer matrix thin film modelling. An allowance is made for the depletion region, but we presume the field is uniform across all wells, and that the results for the 95 well structure can be linearly extrapolated down to fewer wells. The Quantum Confined Stark Effect (QCSE) varies quadratically with voltage, giving a bigger absorption change at higher fields, but counterbalanced by a decreasing and spreading exciton.[3] Thus there exists an optimum change in field per well which gives the largest change in absorption. Allowing a maximum voltage swing of 0-5V, structures having different numbers of wells are modelled. These results are included in figure 2a. A maximum reflectivity change ΔR of 22% is obtained across 63 wells. Because of the nature of the QCSE, better modulation is to be expected at higher fields; thus applying a pre-bias should improve matters. Allowing 5V modulation on a bias of 5V a maximum reflectivity change ΔR of 35% is predicted for 65 wells, as shown in figure 2b.

3. Optical Cavity Modulator
We will now consider what improvement can be obtained by incorporating the active region in an optical cavity. The back mirror, as before, is a gold coating. The front mirror is formed by including a 1/4λ stack between the *pin* layers and the strain relaxation layers, as indicated in fig 1. The mirror layers contain an Indium content to maintain the strain balance. As the back mirror is fixed, our principal degrees of freedom in the design are the number of wells and the reflectivity of the front mirror, determined by the number of mirror periods. One further issue is the operating wavelength with respect to the low and high field spectra. Figure 3 shows examples of low and high field absorption spectra and the resultant difference $\Delta\alpha$. For the simple absorption modulator, described above, the optimum point is at the absorption difference maximum, and initially we took this as the operating point for the optical cavity designs. However empirical modelling found that a larger

change in reflectivity could be obtained by shifting the operating point slightly to the long wavelength side, as indicated. This may be understood in that the slight decrease in absorption change is more than offset by the reduced absorption of the low field curve, giving a higher reflectivity with no modulation applied. Operating at this point, structures were simulated with different numbers of wells and mirror periods. Best results are summarised in figure 2a (no bias) and 2b (5V bias). With no bias (fig. 2a) the largest reflectivity change was obtained using 5 mirror periods. As can be seen a significant improvement is achieved over the no mirror, i.e. simple double pass case. Figure 2b shows the equivalent curves with 5V bias. The optimum performance is now achieved with only 2 mirror periods, and is even better. The main point to take from these curves is that the actual reflectivity change can be enhanced by a factor of ~50% as compared to the no-cavity case.

4. Uniformity and Speed Issues

The largest concern with such Fabry-Perot optical cavity structures is the resultant tolerance to growth uniformity that is required. In structures grown by MBE or MOCVD there are actually two issues. One is the absolute accuracy of the thickness. Fortunately this can be addressed in this design by post-growth processing of the wafer before gold mirror deposition.[4] The second is non-uniformity across a wafer, resulting from growth geometry etc, and this generally cannot be removed subsequently, and thus must be tolerated. In order to study this, we modelled the expected change in reflectivity when the actual thickness deviated from the ideal design. Indicative results for a typical 1.4 um cavity are presented in figure 4. Surprisingly broad tolerance is obtained. The resultant change in reflectivity remains above the best possible no-cavity design, even for variations of ±20 nm, which corresponds to ±1.5% of cavity thickness. This is within what may be achieved in good growth for the across-wafer non-uniformity for a significant fraction of a wafer.

From the above results it is clear that a significant enhancement of change in reflectivity can be obtained by the inclusion of one or two mirror periods of front mirror, giving the well known asymmetric Fabry-Perot modulator structure. Furthermore that is technically feasible to produce such structures. A possible problem with such a design is that it leads to a reduction in the number of wells. This will impact on speed, due to the increased capacitance of the *pin* structure, and also effect operation as a detector. The modulator may be modelled as a simple capacitor of thickness equal to the MQW intrinsic region. Taking typical values of device diameter of ~20um, and an average permitivity of $12\varepsilon_o$, then changing the number of wells from 95 to 60 increases the capacitance from ~30 fF to ~40 fF. Although a measurable increase, the associated capacitance of the contacts and underlying circuitry would also have to be included before the actual impact of such an increase could be assessed. The capacitance only begins to increase significantly for less than 40 wells. For detector operation the reduction in absorption resulting in the reduced number of wells is offset by the cavity structure, actually resulting in a net gain in absorption.

5. Very Low Voltage Operation

The above results are given for 5V operation. To take account of the trends to lower voltage operation of CMOS circuitry the possible performance at lower voltages is examined. In each case the bias is equal to the modulation voltage, effectively operating from V volts to 2V volts. As before the variables in design modelling are the number of wells and the internal mirror reflectivity, *i.e.* the number of mirror periods. The structures yielding the best reflectivity change in each case are summarised in table 1.

Voltage (and bias)V	No. of wells	No. of mirror periods	Max ΔR%
5	65	2-3	49
3.3	43	4-5	40
2.5	35	6-7	32
2	26	7	27
1.8	24	7-8	24
1	13	9	11

Table 1. Summary of structures yielding best reflectivity changes for low voltages.

The general trend to note is that as the voltage is reduced the number of wells decreases, so as to maintain high fields. To make up for the loss in absorption the mirror reflectivity increases, as indicated by the increasing number of mirror periods. The resulting higher finesse cavities ultimately lead to decreasing maximum reflectivity change ΔR, due to the increasing influence of the non-zero low field absorption. These results indicate that this approach cannot be extrapolated indefinitely, as decreasing ΔR is accompanied by increasing complexity and sensitivity to non-uniformity.

6. Conclusions

In conclusion we can state that modelling based on real experimental InGaAs MQW absorption curves indicates that a significant improvement of ~50% can be achieved in the change in reflectivity for 5V operation by the use of an asymmetric Fabry-Perot cavity structure. The resultant non-uniformity restrictions are within current best practice, given post-processing to adjust the absolute thickness prior to mirror deposition. The resultant reduction in the number of quantum wells will not significantly reduce speed or detector operation. Operation at lower voltages is possible, but performance and tolerance to non-uniformity decreases. These results will be verified against test structures now being grown.

7. Acknowledgements

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8. References

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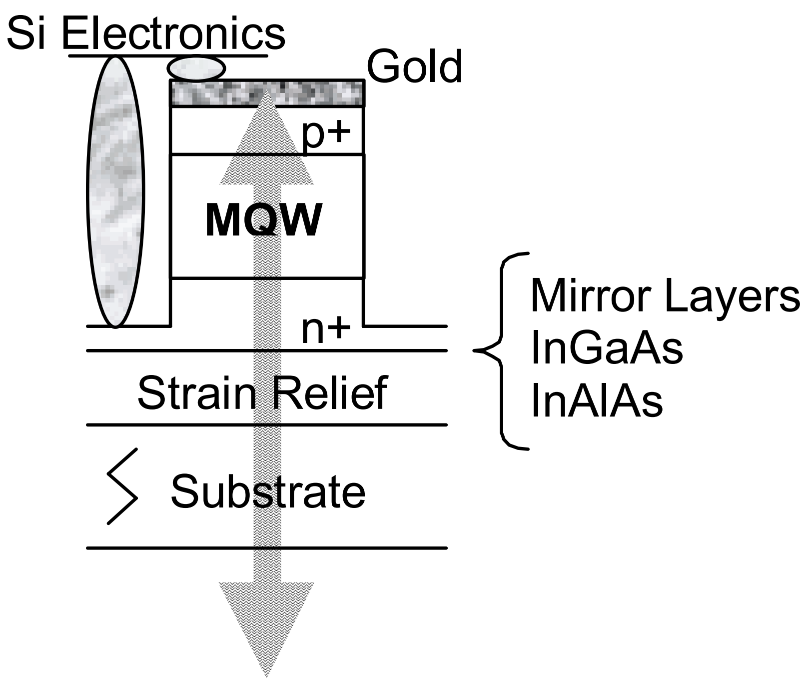
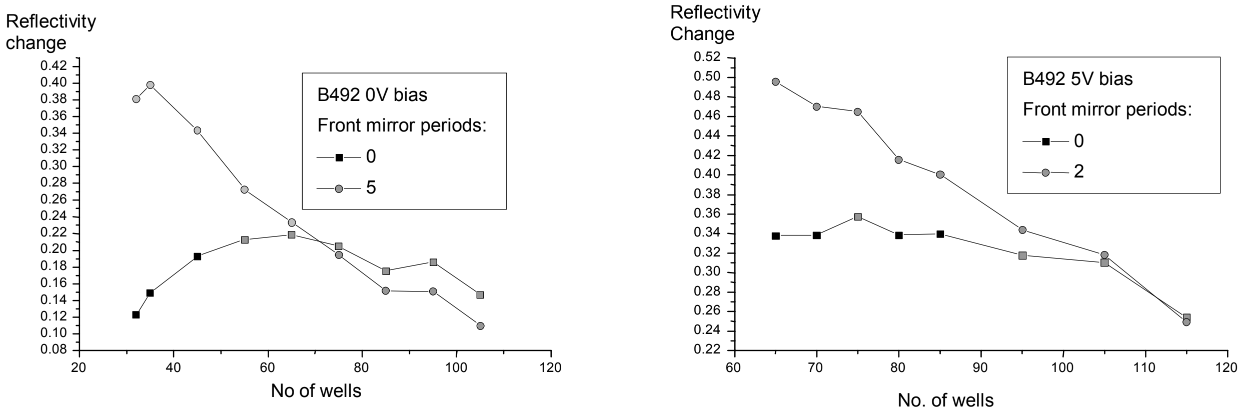


Figure 1. Structure of the modulator



(a) **(b)**

Figure 2. Reflectivity change versus number of wells for 5V modulation and (a) no bias with 0 and 5 mirror periods, and (b) 5V bias for 0 and 2 mirror periods.

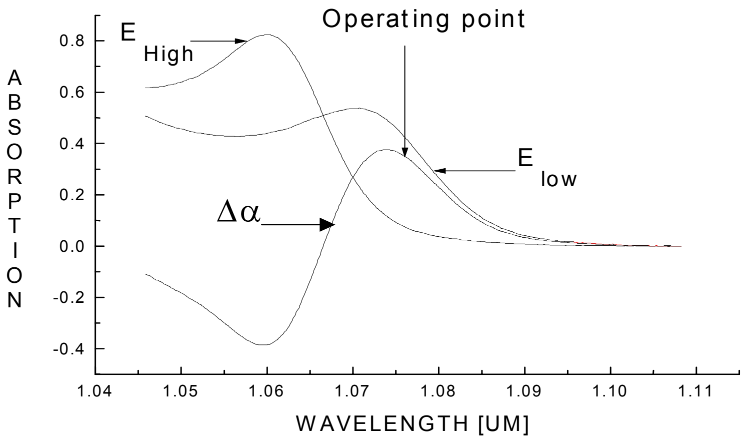


Figure 3 Illustration of low and high field absorption spectra, and the difference spectrum $\Delta\alpha$.

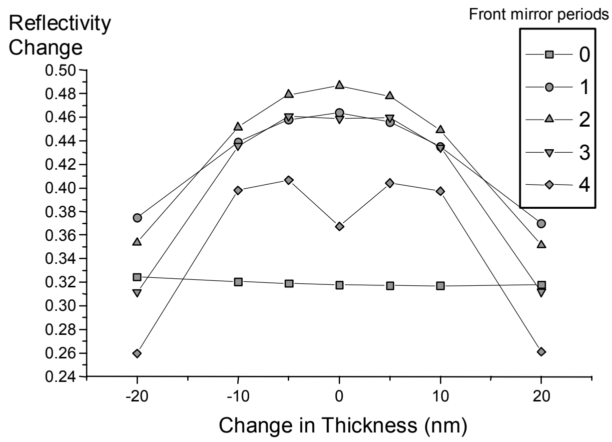


Figure 4. Reflectivity change versus thickness variation for increasing number of front mirror periods for a 1.4 micron optical cavity.