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Post-growth tuning of inverted cavity InGaAs/AlGaAs spatial light modulators using phase compensating dielectric mirrors

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A novel method is demonstrated for the correction of cavity thickness deviations imposed by technological limitations in the growth process of a resonant cavity spatial light modulator. This method is based on cavity phase compensation through the use of an externally-deposited dielectric Bragg mirror and provides an effective means of optimizing the device characteristics. In particular, such mirrors can significantly relax otherwise stringent epitaxial growth requirements in the fabrication of hybrid silicon/compound-semiconductor spatial light modulators incorporating Fabry–Perot cavities. We further demonstrate deposition of a conductive, index-tunable indium tin oxide (ITO) antireflection coating that is designed to maximize the contrast ratio and throughput of the inverted-cavity modulator configuration. © *1995 American Institute of Physics.*

Asymmetric Fabry–Perot (ASFP) III–V compound semiconductor reflection spatial light modulators (SLMs) exhibit contrast ratios of greater than 1000:1,[1] dynamic ranges of ∼65%,[1,2] insertion losses of less than 2 dB,[3] and VLSI-compatible operating voltages on the order of 1 to 2 V.[4,5] These results, however, have not yet been achieved simultaneously in a single structure, and have typically been limited to individual pixels selected from large areas of as-grown wafers containing layer thickness and composition nonuniformities inherent in the growth process. Absolute control of the Fabry–Perot cavity thickness and composition is critical in the fabrication of devices utilizing resonant cavities because small variations of less than ±1% can translate into significantly reduced device performance characteristics.[6,7] In addition, the buried high-reflectivity epitaxially grown Bragg mirror characteristic of resonant-cavity-based modulators is a *soft* mirror with a very steep phase dispersion (Fig. 1), such that growth-induced variations in the mirror parameters can cause the effective plane of reflection to deviate from the cavity-mirror interface.[8] Finally, accurate design of the total cavity phase prior to growth is complicated by the fact that the optical path length within the multiple quantum well (MQW) structure can only be estimated at best, typically by using a mean refractive index weighted by the constituent material con-centrations.[9]

In this letter, we experimentally demonstrate post-growth optimization of the cavity phasing condition in an otherwise unusable (low contrast ratio) active ASFP MQW spatial light modulator device structure by using an externally deposited phase-tunable broadband *dielectric* Bragg mirror. This novel *ex situ* phase compensation method utilizes the inherent wavelength dispersion of the phase shift upon reflection from a distributed (Bragg) mirror, and allows for both positive as well as negative phase adjustments.

The magnitude of the phase shift obtainable within the reflectivity bandpass depends on both the index difference between the mirror layers and the total number of periods. The large index differences afforded by dielectric materials allow the external mirror to achieve higher reflectivities and broader bandwidths using fewer periods as compared with conventional semiconductor mirrors, which rely on smaller index differences (Fig. 1). This broadband nature makes it possible to implement desirable phase corrections while simultaneously retaining high reflectivities. For MQW asymmetric modulator fabrication, however, only a small shift in the position of the Fabry–Perot minimum is typically required after growth of the cavity to achieve optimum separation with respect to the exciton. The currently achievable precision of the *ex situ* compensation technique has previously been demonstrated to correspond to ±10° in cavity phase, which is equivalent to a ±0.2% change in cavity thickness or to a ±20 Å shift in the Fabry–Perot minimum.[10]

The best reflection-geometry SLM device performance

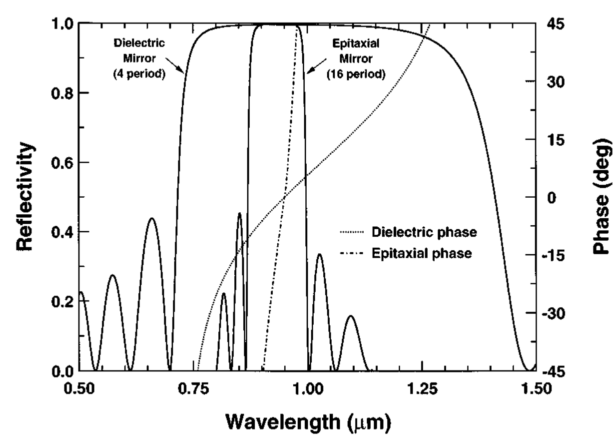

FIG. 1. Comparison of the reflectivities and phase dispersions of a four-period dielectric Bragg mirror (MgF_2, Sb_2S_3) and a sixteen period MBE-grown internal mirror (AlAs,GaAs) both centered at 0.95 μm.

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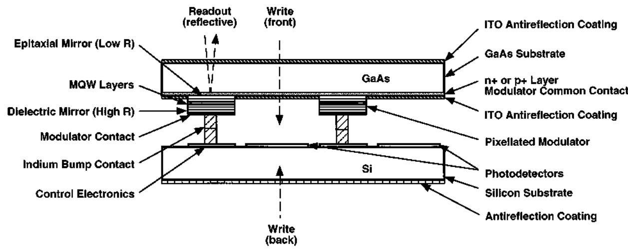

FIG. 2. Hybrid face-to-face SLM design with the modulator fabricated on a GaAs substrate and the drive electronics on a Si substrate. The two substrates are bump contacted on a pixel-by-pixel basis. The design shows the inverted modulator structure with an external high reflectivity dielectric Bragg mirror, transparent substrate, and ITO antireflection coatings.

characteristics achieved to date[1–5] have been primarily implemented in the $Al_xGa_{1-x}As/GaAs$ MQW system grown on opaque GaAs substrates (with typical operating wavelengths of 0.85 μm). However, for Si-based stacked multichip module applications,[6] dense vertical interconnections are difficult to implement without the use of through-substrate vias. To circumvent the need for such vias we have proposed an inverted *face-to-face* hybrid architecture SLM design using strained layer MQWs (such as $In_xGa_{1-x}As/Al_yGa_{1-y}As$) on a GaAs substrate in conjunction with through-substrate readout.[6] In such inverted structures,[11] the MQW exciton resonance can be placed at longer wavelengths ($\sim$0.96 μm for $x\sim0.18$ and $y\sim0.25$), far enough away from the band edge of semi-insulating (SI) GaAs to result in negligible substrate absorption.[11] The Si photodetectors can be accessed either through the GaAs or the (thinned, backside illuminated) Si substrates as shown in Fig. 2, and the drive circuitry thus requires only face-to-face bump-type contacts to the modulator array.[6]

In addition to providing for cavity phase compensation, dielectric Bragg mirrors offer further significant advantages when used in the face-to-face architecture. The inverted SLM design allows for replacement of the internal high-reflectivity mirror with an external dielectric Bragg mirror, which relaxes the epitaxial growth requirements (by about 3 μm) and thus enhances the processing yield. In order to maximize both the throughput and contrast ratio, and to eliminate multiple internal reflections in the substrate, an antireflection coating is required on the front (growth) face of the pixelated substrate in device-free regions, as well as on the back (light incident) face (Fig. 2).

Operation of a normally-on ASFP modulator involves a red shift of the exciton and a blue shift of the Fabry–Perot (FP) minimum (due to the quantum confined Stark effect) so that bias-voltage-induced coincidence of the two features results in a reflectivity null at the operating wavelength. Achievement of the maximum contrast ratio dictated by the available biased absorption requires an optimum separation between the unbiased exciton and the FP mode. In addition, a strict cavity phasing condition must be met in order to obtain high contrast ratios in ASFP modulators. Fundamental considerations dictate[6,12] that for the InGaAs/AlGaAs-on-GaAs system the roundtrip optical cavity thickness must be an even multiple of π in order to produce a cancellation of the reflected field.

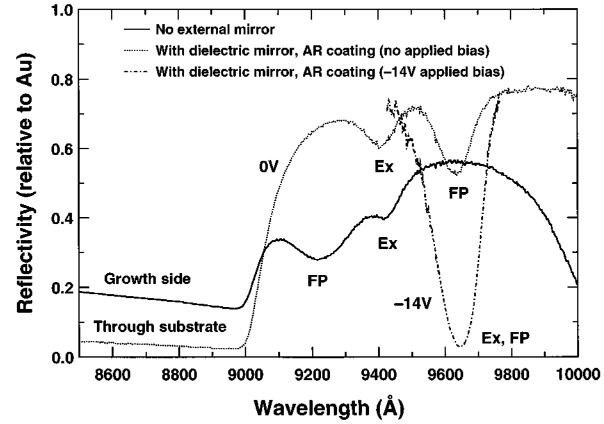

FIG. 3. Measured reflectivities as a function of wavelength for the selected-pixel ASFP modulator before deposition of the external mirror (as measured from the growth face), and for the same modulator including the AR coating and dielectric mirror both with and without bias (as probed from substrate side).

We have previously demonstrated that externally-deposited dielectric mirrors can be used to fine tune the location of the Fabry–Perot minima in a bare GaAs resonant cavity without an active MQW modulator.[10,12,13] In order to further demonstrate the effectiveness of the post-growth method of cavity phase compensation, we describe herein an experiment in which an intentionally chosen fully-nonfunctional modulator pixel from the edge region of an as-grown wafer,[11] as determined by reflectivity measurements after growth, was made fully functional by the *ex situ* deposition of an appropriately phased dielectric mirror. The structure incorporated a Bragg reflector ($R=62\%$) that consisted of 5.5 periods of Si-doped GaAs (702 Å) and AlAs (830 Å) grown on a both-sides-polished semi-insulating GaAs(100) substrate. A 60 Å GaAs transition layer was grown beneath the modulation region, which consisted of 50 periods of strained layer $In_{0.17}Ga_{0.83}As/Al_{0.3}Ga_{0.7}As/GaAs$ MQWs followed by a 1700 Å buffer layer. This final layer was chosen in order to achieve a roundtrip cavity phase condition of 14π, corresponding to a total thickness of 1.03 μm and an FP minimum at $\lambda_0 = 9800$ Å.

Reflectivity measurements (relative to a freshly deposited Au mirror) were performed on different regions of the wafer using an Ar-ion pumped Ti-sapphire laser in the wavelength range of 8500–10 000 Å, incident from the growth face. In the chosen nonfunctional pixel near the edge of the wafer, the location of the FP minimum (9215 Å) was determined to be on the opposite (short wavelength) side of the exciton at 9415 Å, as shown in Fig. 3. Four factors potentially contribute to this offset: (i) the cavity optical path length (at the edge of the wafer) was less than the design value, (ii) a phase offset existed due to inaccuracies in the internal Bragg mirror thicknesses, (iii) MQW layer thickness and composition variations contributed to an offset in the absolute position of the exciton, and/or (iv) the pregrowth estimate of the mean weighted cavity index used to design the cavity thickness was inaccurate.

In order to reposition the FP mode on the proper (longer wavelength) side of the exciton and thus achieve the optimal separation (200 Å), we electron-beam deposited an inverted dielectric Bragg mirror with a peak reflectivity of $R=98\%$, consisting of eight alternating quarter-wave layers of MgF_2 and Sb_2S_3 with indices $n_1=1.37$ and $n_2=2.98$, respectively, and designed to be centered at 9615 Å. A low deposition rate of 2 Å/s at room temperature and the use of glow discharge (to enhance film adherence) provided a very high quality mirror centered at the desired wavelength.

A single layer quarter-wave indium tin oxide (ITO) antireflection coating was sputter-deposited onto the rear face,[13] and was tuned in index and thickness so as to achieve a minimum at the point where the FP minimum and the exciton coincide under applied bias. The ITO index of refraction can be tuned throughout the range 1.9 to 2.0 by varying the oxygen content in the sputtering gas and/or the percentage fraction of SnO_2 in the target. This makes it possible to match the exact antireflection coating condition for the index of the dispersive GaAs substrate at a particular wavelength, simultaneously providing a conductive ground plane. Using an ITO target with a composition of 90% In_2O_3 and 10% SnO_2 together with an oxygen partial pressure of 10^{-6} Torr, an absolute reflectivity of 0.000 25 at 0.95 μm was achieved.[13] This reflectivity allows for a maximum observable contrast ratio of 4000:1, and hence the overall device contrast ratio is determined primarily by the modulator on/off reflectivity ratio.

A through-substrate measurement after deposition of the mirror and AR coating indicated that the exciton remained unshifted, but that the FP minimum was now located at 9636 Å (Fig. 3). The inverted-layer ordering of the mirror induced a π phase shift and switched the FP mode minimum to the longer wavelength side of the exciton, within 21 Å of the optimal separation (200 Å). At an applied reverse bias of -14 V, the reflectivity for the normally-on modulator decreased from 48% to 3%, giving a contrast ratio of 16:1, a dynamic range of 45%, and an insertion loss of 3 dB.

The phase-compensation method described herein is based on proportional scaling of *all* of the layers in an externally deposited dielectric mirror stack with respect to the quarter-wave thickness.[10] The advantage of this approach for our application lies in its capability for either gross or fine *ex situ* adjustments depending on whether a normal (shallow phase slope centered about 0) or inverted (steep phase slope centered about π) Bragg mirror configuration is employed. Phase compensation using an externally deposited dielectric mirror may also be achieved for either the inverted or noninverted configurations by varying the optical thickness of only *one* of the layers of the mirror stack from 0 to $\pm\pi/4$, thus making it possible to obtain phase changes ranging from 0 to $\pm\pi$ while maintaining the high mirror reflectivity. Use of this technique results in steeper phase slopes than those characteristic of the proportional scaling approach for a comparable change in total mirror thickness, which may prove useful in certain applications. A related method, for implementing *in situ* cavity corrections in a vertical cavity surface-emitting laser (VCSEL) by tuning a single layer within the upper epitaxial AlAs/AlGaAs mirror, has been demonstrated in the AlGaAs/GaAs system.[14] Either variation of the post-growth phase compensation technique can be used in conjunction with conventional chemical etching techniques,[11] if desired, subject to the constraint that etching techniques can subtract from but not add to the phase of a cavity. The use of chemical etching in conjunction with a dielectric mirror for cavity mode positioning in VCSELs has been demonstrated in the InGaAs system.[15]

In summary, we have demonstrated a method for post-growth *ex situ* phase compensation of an ASFP modulator using an externally deposited dielectric Bragg mirror. The use of this technique enabled us to change the characteristics of the as-grown structure and to thus salvage an otherwise useless modulator. Key features of this technique include: (i) post-growth probing of the modulator structure can be performed to determine if repositioning of the FP minimum is required, (ii) the cavity can be accurately tuned using either an inverted mirror (centered at π) with steeper phase dispersion or an noninverted mirror (centered at 0) with shallower phase dispersion (for production applications after the variations in a given growth process have been minimized[11]), (iii) bipolar changes in cavity phase are easily implemented, and (iv) the mirror can be repeatedly removed (using dilute HCl) and redeposited if necessary.

Post-growth cavity tuning by incorporating externally deposited phase compensating dielectric mirrors can also be applied to traditional asymmetric cavity MQW modulators based on the AlGaAs/GaAs system,[16] in which low-reflectivity dielectric mirrors can replace the usual air-GaAs top interface, optimizing the cavity finesse as well as phase tuning the resonant cavity.

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[1] D. S. Gerber, R. Droopad, and G. N. Maracas, IEEE Photonics Technol. Lett. **5**, 55 (1993).
[2] K.-K. Law, M. Whitehead, J. L. Merz, and L. A. Coldren, Electron. Lett. **27**, 1863 (1991).
[3] B. Pezeshki, D. Thomas, and J. S. Harris, Jr., IEEE Photonics Technol. Lett. **2**, 807 (1990).
[4] K.-K. Law, L. A. Coldren, and J. L. Merz, IEEE Photonics Technol. Lett. **3**, 324 (1991).
[5] R. H. Yan, R. J. Simes, and L. A. Coldren, IEEE Photon. Technol. Lett. **2**, 118 (1990).
[6] C. Kyriakakis, Z. Karim, J. H. Rilum, J. J. Jung, A. R. Tanguay, Jr., and A. Madhukar, Technical Digest, OSA Topical Conference on Spatial Light Modulators and Applications, Incline Village, NV (1990).
[7] K.-K. Law, J. L. Merz, and L. A. Coldren, J. Appl. Phys. **72**, 855 (1992).
[8] D. I. Babic and S. W. Corzine, IEEE J. Quantum Electron. **28**, 514 (1992).
[9] M. Whitehead, G. Parry, and P. Wheatley, IEE Proc. **136**, 52 (1989).
[10] Z. Karim, C. Kyriakakis, A. R. Tanguay, Jr., L. Chen, K. Hu, and A. Madhukar, Appl. Phys. Lett. **64**, 1 (1994).
[11] K. Hu, R. Cartland, L. Chen, K. Kaviani, P. Chen, and A. Madhukar, Tech. Dig. Opt. Soc. Am. **6**, 170 (1993).
[12] C. Kyriakakis, Ph.D. dissertation, University of Southern California, 1993.
[13] Z. Karim, Ph.D. dissertation, University of Southern California, 1993.
[14] K. Bacher, B. Pezeshki, S. M. Lord, and J. S. Harris, Jr., Appl. Phys. Lett. **61**, 1387 (1992).
[15] P. A. Evaldsson, G. W. Taylor, P. W. Cooke, S. K. Sargood, P. A. Kiely, and D. P. Docter, IEEE Photonics Technol. Lett. **5**, 634 (1993).
[16] R. A. Morgan, G. Livescu, L. M. F. Chirovsky, M. W. Focht, and R. E. Leibenguth, Opt. Lett. **17**, 423 (1992).