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Strain Accommodation in Mismatched Layers by Molecular Beam Epitaxy: Introduction of a New Compliant Substrate Technology

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Compliant substrates allow a new approach to the growth of strained epitaxial layers, in which part of the strain is accommodated in the substrate. In this article, compliant substrates are discussed and a new compliant substrate technology based on bonded thin film substrates is introduced. This technology has several advantages over previously published methods, including the ability to pattern both the top and bottom of the material. A new concept enabled by this compliant substrate technology, *strain-modulated epitaxy,* will be introduced. Using this technique, the properties of the semiconductor material can be controlled laterally across a substrate. Results of two experiments are presented in which low composition $In_xGa_{1-x}As$ was grown by molecular beam epitaxy on GaAs compliant substrates at thicknesses both greater than and less than the conventional critical thickness. It was found that for $t > t_c$, there was an inhibition of defect production in the epitaxial films grown on the compliant substrates as compared to those grown on conventional reference substrates. For $t < t_c$, photoluminescence and x-ray diffraction show the compliant substrates to be of excellent quality and uniformity as compared to conventional substrates.

Key words: Compliant substrates, growth kinetics, molecular beam epitaxy (MBE), strain

INTRODUCTION

The ability to produce strained semiconductor structures has dramatically enhanced device performance and design flexibility. The production of reliable strained layer devices is limited, however, by the maximum strain which can be accommodated in a lattice-mismatched overlayer before defects are produced to reduce the strain energy. A new approach to strained layer growth, in which the strain is partially accommodated in a *compliant substrate,* as well as in the lattice-mismatched overlayer, has been proposed and demonstrated.[1,2] The possibility of growing on such compliant substrates, as opposed to conventional substrates, opens the door to a large number of applications. Since the compliant substrate acts to extend the conventional critical thickness of a mismatched overlayer, it enables the growth of new materials that would otherwise be crippled by defects due to strain relaxation. Additionally, compliant substrates can be used to engineer strain distributions in thin films during and after growth.

Previous research groups have grown on GaAs compliant substrate platforms which remain attached to conventional substrate material at the corners[1] and Si compliant substrates using silicon-on-insulator (SOI) material.[2,3] In this article, we present a new compliant substrate technology based on thin film substrates, which are comprised of epilayers which have been separated from the growth substrate. These thin film substrates can be formed through epitaxial lift-off or by total substrate removal. Both cases result in thin film, compliant semiconductor substrates, which offer advantages over the previously reported methods. In addition to the ability to extend the critical thickness with compliant substrates, we propose a means of attaining lateral control of semiconductor properties with this compliant substrate technology. Our approach is based on the new concept of strain-modulated epitaxy which is enabled by bottom-patterned, compliant substrates. Our initial demonstrations of the growth of strained InGaAs on thin film GaAs compliant substrates and the results we have obtained are summarized below.

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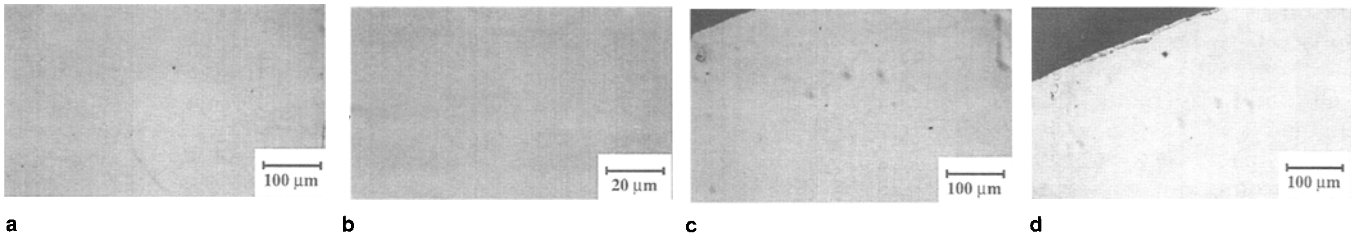

Fig. 1. Representative Nomarski photographs of compliant substrates: (a) and (b) are demonstrations of good surface morphology before and after growth, respectively; (c) and (d) show an example of the size and extent of bubble formation before and after growth, respectively.

COMPLIANT SUBSTRATE TECHNOLOGY

The objective of using compliant substrates is to reduce the strain in a mismatched overlayer by accommodating the strain in a thin compliant substrate. In the case of strained layer growth on a conventional 500 µm thick substrate, the epitaxial layer is much thinner than the substrate, and therefore virtually all of the strain resides in the epitaxial layer. On the other hand, the thickness of the compliant substrate is on the order of that of the epitaxial layer. In this case, the strain produced during growth will be partitioned between the substrate and the lattice-mismatched epitaxial layer. Hirth et al.[4] have theoretically calculated the strain partitioning in a structure containing two or more thin layers with no conventional substrate. Neglecting the difference of the elastic coefficients of the materials, the new strain in the epilayer is approximately[4]

$$\varepsilon_f = \frac{h_s}{h_f + h_s}\varepsilon_0$$

where ε_f is the partitioned strain in the epitaxial film, ε_0 is the total misfit strain, and h_s and h_f are the thicknesses of the substrate and the film, respectively. The ability of the substrate to accommodate part of the total strain of the system leads to applications in two different growth regimes. In the first regime, the substrate and film share the strain elastically; in the second regime, the substrate relaxes *before* the epitaxial layer, allowing for reduced defect density in the mismatched overlayer compared to the case of a thick substrate. In both of these growth regimes, the conventional critical thickness of the epitaxial layer is effectively extended.

Research on compliant substrates was pioneered by Y.H. Lo.[1] His group has grown InGaAs films on compliant platforms as thin as 800Å, and designed static and dynamic models to explain the effect of the compliant substrate on the critical thickness. Their models indicate that, for a thin enough substrate, a mismatched layer of infinite thickness can be grown. They also determined that when InGaAs layers greater than the critical thickness were grown on both conventional substrates and thin substrates, fewer defects were produced in the InGaAs grown on the thin substrates as observed by atomic force microscopy and x-ray diffraction. In addition, Powell et al.[2] have grown SiGe films on 650Å Si compliant substrates utilizing SOI technology. They found that, upon post growth annealing, defects were initially produced in the Si substrate. The published work on compliant substrates to date has concentrated on the growth of films greater than the critical thickness. Therefore, the findings regarding the role of the compliant substrates in strain accommodation are based on measured differences in defect production.

The compliant substrate technology presented herein is different than that of previous approaches because it uses bonded thin film compliant substrates. These thin film substrates can be fabricated by epitaxial lift-off (ELO)[5] or by total substrate removal.[6] In either case, there are one or more layers grown between the material of interest and the growth substrate, which can be used with selective and/or stop etches to separate the growth substrate from the epilayers, thus producing the thin film substrate. In epitaxial liftoff, a layer is selectively etched away, effectively separating the thin film from the host substrate. In total substrate removal, the substrate is completely etched away, leaving only the thin film.

In recent years, epitaxial lift-off and substrate removal have emerged as important enabling technologies for multi-material integration.[7] Thin film photodetectors, lasers, LEDs, modulators, and solar cells have all been integrated onto dissimilar substrates, and, in many cases, performance of these devices has been enhanced due to the access to the bottom of the device during the fabrication process. The ability to process both the top and bottom of a device, paired with the flexibility of integrating different material systems without the difficulties of growing them on the same wafer, has led to many demonstrations of GaAs-and InP-based devices bonded to a variety of substrates including silicon, InP, and glass. Thus, thin film integration is a well established technology and also a natural method for producing compliant substrates. The production of thin (~ hundreds of Å), large area (~cm^2) thin film materials have been demonstrated, and the fabrication approach is consistent with patterning the bottom of the compliant substrate for strain-modulated epitaxy.

All of the compliant substrates used in these experiments were made using epitaxial lift-off. The wafer initially consisted of 2000Å AlAs followed by 1–2 µm GaAs layer, for the thin film substrate, grown by molecular beam epitaxy (MBE) on a conventional GaAs substrate. The sample was covered with Apiezon W black wax and submerged in a 10% HF solution for several hours. During this time, the AlAs layer was selectively etched, leaving the GaAs layer attached to the black wax. This film was attached to an arbitrary substrate by bringing the two into contact and allowing them to dry. The black wax was then removed in TCE, and the resulting compliant substrate was cleaned and processed using standard processing techniques.

The compliant substrates have features that are artifacts of the fabrication process which may include small blisters under the film and other nonuniformities. It is possible to have very high quality films, although it is important to assess the extrinsic effects associated with the compliant substrates (morphology, strain uniformity, etc.). To date, two groups have grown on thin films.[8,9] Yablonovich et al.[8] reported excellent quality and uniformity in their grown layers on bonded thin film substrates, and, although they reported the presence of blisters under the film, they found that the blisters could be partially alleviated with a slow vacuum bake. Some representative Nomarski photographs of the thin substrates used in our experiments are shown in Fig. 1. The first pictures show that excellent quality can be attained by using the ELO process, where Fig. 1a shows the thin film compliant substrate before growth, and Fig. 1b shows the morphology of the as-grown sample in essentially the same spot. The bottom pictures demonstrate the size and extent of the blisters which are sometimes observed from the process. Figures 1c and 1d show the representative blisters before and after growth, respectively. In the samples used in these experiments, the blisters were limited to the areas at the edge of the sample. After growth, there was rarely any noticeable change in the blisters. Improvements in thin film substrate processing and bonding should, in time, lead to blister-free thin film compliant substrates.

The bond which holds the thin film substrate to the mechanical host has been labeled Van der Waals bonding, but in actuality the bond is a native oxide inter-layer.[10] The strength of this bond has been characterized to be between rigid and weak,[11] meaning that the bond has to overcome some activation energy at the interface before it will be weak enough to allow slip between the compliant substrate and the mechanical host substrate.

EXPERIMENTS

Two sets of growth experiments utilizing compliant substrates were completed. In both experiments, low indium-percentage $In_xGa_{1-x}As$ films were grown simultaneously on GaAs thin film compliant substrates and conventional substrates in a Riber 2300 by MBE. In the first set of experiments, InGaAs layers greater than the conventional critical thickness were grown and the role of the compliant substrate was inferred from defect production. In doing this, we assumed that the initial defect density of the two substrates was the same. In the second set of experiments, InGaAs films with thicknesses less than the conventional critical thickness were grown. In these experiments, the properties of elastically deformed films were measured directly. This experiment allowed us to compare the quality of growth on conventional substrates and compliant substrates. These growths were characterized by low temperature photoluminescence (PL), double crystal x-ray diffraction, and Nomarski microscopy.

The design of the first experiment is shown in Fig. 2. $In_{0.1}Ga_{0.9}As$ films were grown in two consecutive runs at a substrate temperature of 520°C. Compliant substrates 2500 or 5000Å thick, as well as 500 μm thick reference substrates, were used in each run. The compliant substrates were made by bonding epitaxial lift-off thin film GaAs to the same GaAs mechanical host substrates to which they were previously attached. In the first growth, the film thickness was 4000Å, and in the second growth, the film thickness was 2000Å.[12] Nomarski photographs of the substrates are shown in Fig. 3. Figures 3a and 3b are photographs of the 4000Å thick InGaAs on the reference and 5000Å substrates, respectively. Similarly, Figs. 3c and 3d are micrographs of the 2000Å thick InGaAs on the reference and 2500Å substrates, respectively. The 4000Å layer on the reference has pronounced cross-hatching, whereas the 2000Å layer on the reference has dislocations oriented in one direction only. In both cases, the epitaxial film grown on the thin film substrate has a lower density of defects than that observed for growth on the conventional substrates. The 4000Å thick InGaAs grown on the thin film substrate exhibited slip lines, whereas, on the 2000Å

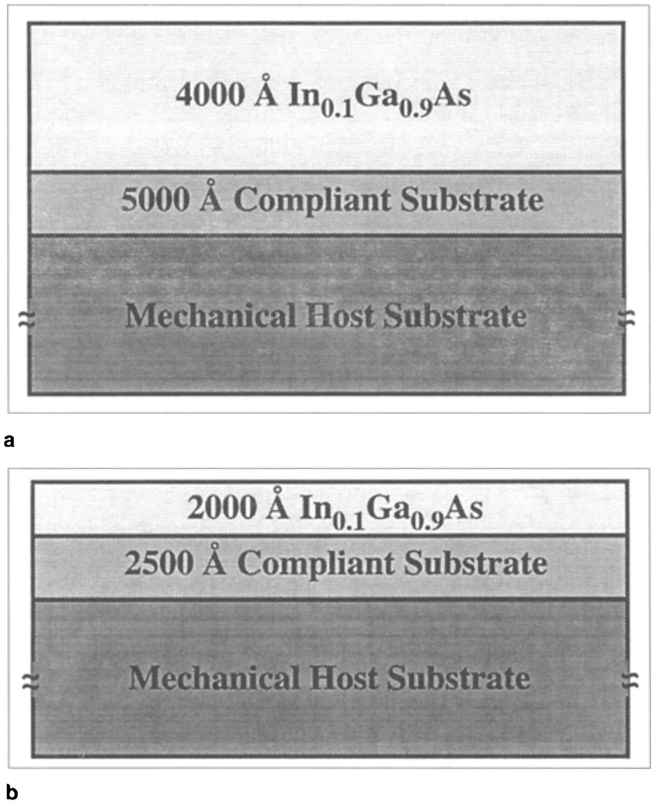

Fig. 2. Structure for Experiment 1: $In_{0.1}Ga_{0.9}As$ (a) 4000Å thick and (b) 2000Å thick grown on GaAs compliant substrates which are bonded to GaAs mechanical host substrates.

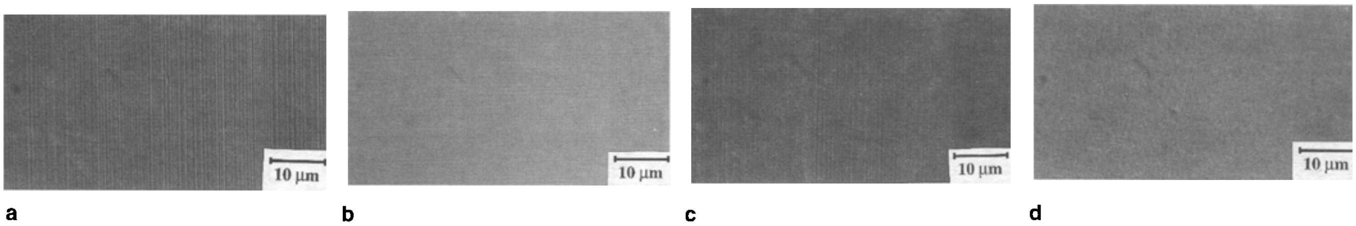

Fig. 3. Nomarski photographs of $In_{0.1}Ga_{0.9}As$: (a) and (b) are photographs for 4000Å $In_{0.1}Ga_{0.9}As$ grown on a 5000Å compliant substrate and conventional substrate, respectively; (c) and (d) are photographs for 2000Å $In_{0.1}Ga_{0.9}As$ grown on a 2500Å compliant substrate and conventional substrate, respectively. In both cases, there is an inhibition of defect production on the compliant substrate.

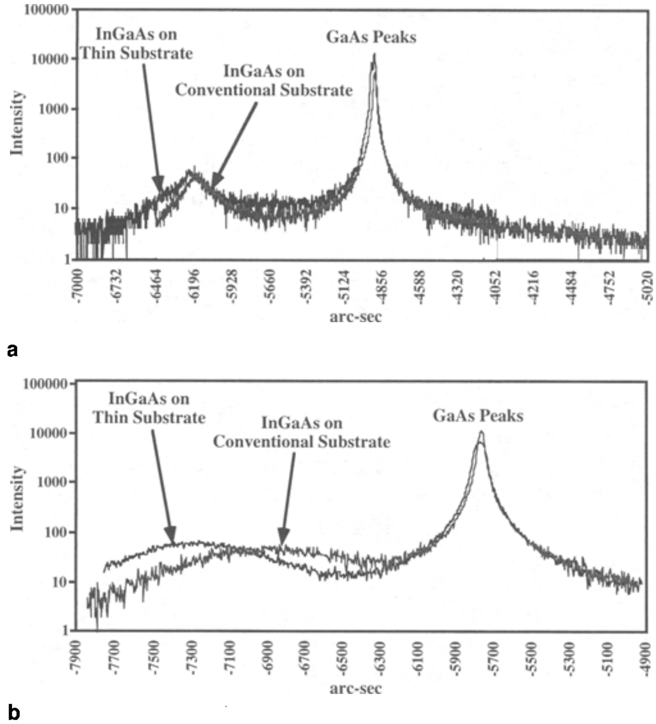

Fig. 4. Double crystal x-ray diffraction. (a) 2000Å $In_{0.1}Ga_{0.9}As$ on 2500Å and conventional substrates, and (b) 4000Å $In_{0.1}Ga_{0.9}As$ on 2500Å and conventional substrates. The data confirms that there is an inhibition of defect production on the compliant substrates.

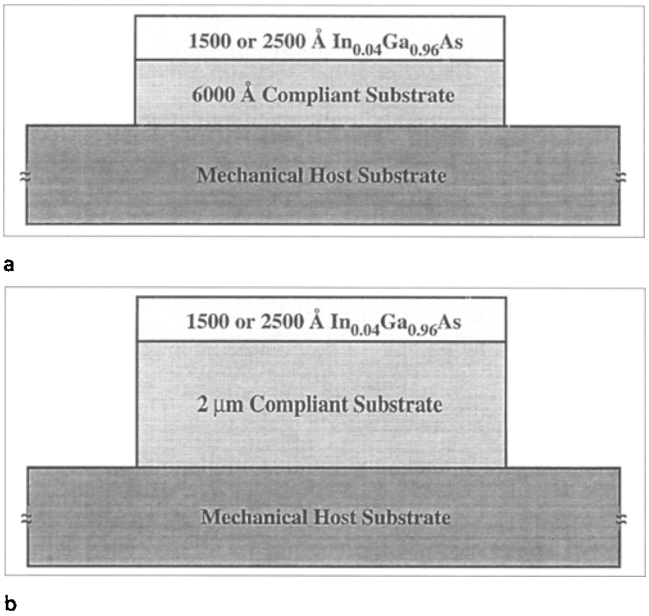

Fig. 5. Structure for Experiment 2. $In_{0.04}Ga_{0.96}As$ 1500 and 2500A thick grown on (a) 6000Å and (b) 2 µm thick compliant substrates which are bonded to GaAs mechanical host substrates.

thick InGaAs on the thin film substrate, these defects were not visible with Nomarski.

Double crystal x-ray diffraction spectra were taken for the compliant substrate samples at 0 and 180°. No tilt was observed between the compliant and host substrates. The rocking curves for these samples are shown in Fig. 4. Because the substrates are so thin, the large GaAs peak is attributed to the mechanical host substrate. Superimposed in Fig. 4a are the rocking curves for 2000Å InGaAs grown on the thin and reference substrates. The InGaAs peak positions only differ by about 15 arc-sec relative to the GaAs mechanical host peak and have similar full widths at half maximum (FWHM), indicating that both the substrates have similar degrees of strain relaxation. Figure 4b shows the two rocking curves for the 4000Å growth. In this case, the InGaAs on the conventional substrate has shifted 580 arc-sec closer to the GaAs peak and has a 24% larger FWHM than the InGaAs grown on the thin substrate. This indicates that the InGaAs grown on the conventional substrate is of poorer quality than that grown on the thin film substrate. One explanation may be that, for the InGaAs grown on the thin film substrate, part of the strain is accommodated in the thin film substrate. The strain energy in this system would be lower than the case of the InGaAs grown on the conventional substrate, and less likely to relax through dislocations formed in the InGaAs layer.

In the second set of experiments, $In_{0.04}Ga_{0.96}As$ was grown at a substrate temperature of 500°C, low enough to inhibit defect formation,[13] as shown in Fig. 5. In this case, two different thicknesses of ELO substrates, 6000Å and 2 µm, were used in addition to a reference substrate. The compliant substrates were made by bonding the thin film GaAs compliant substrate onto another GaAs mechanical host substrate. The first growth consisted of 1500Å of InGaAs and the second growth consisted of 2500Å of InGaAs. Two samples of each substrate thickness were used so that the uniformity could be noted.

A comparative study between epitaxial layers grown on the 6000Å and 2 µm thin compliant substrates and the conventional GaAs reference was performed for each of the growths using low temperature photoluminescence and double crystal x-ray diffraction. Photoluminescence was performed at both 77 and 4.2 K at several different powers. No peak shifts were observed using either technique, however, useful insight into the characterization of compliant substrates was gained in these experiments. It was determined from (1) that the expected shift in the PL energy for the InGaAs grown on the 6000Å thin compliant substrates was less than the observed growth nonuniformity across the samples, i.e. 5 meV, or less than 0.5% change in In composition. The 2 μm thick compliant substrate was not expected to have any energy shift. Substantial tilt between the compliant substrate and the mechanical host substrate and large FWHM prevented the measurement of peak separations using double crystal x-ray diffraction. We suspect that the tilt arises from the standard (100) ± 0.5° slice tolerance of both the mechanical host substrate and the thin compliant substrate, as well as the possible tilt acquired in the bonding process. The large FWHM is due to the fact that the films are thin and the Si first crystal on the double crystal diffractometer.

While comparing the low temperature PL of the 2 μm and 6000Å thin compliant substrates, it was observed that the spectra were markedly different on the compliant substrates compared to the spectra on the surrounding mechanical host. Experiments are currently in progress to determine the reason for this. However, we speculate that these differences are due to the fact that we are comparing a standard boule-grown substrate with an epitaxial substrate. The spectra of the samples grown simultaneously on the same thickness substrates were always very similar, and, in all cases, the FWHM of the InGaAs-related peak was comparable (~6 meV) on the compliant substrate and the mechanical host. These are indications that the properties of our epitaxial lift-off substrates are uniform and reproducible. These results also indicate that a better comparison could be made between the compliant substrates and the same material before epitaxial lift-off rather than with a boule-grown GaAs wafer.

STRAIN MODULATED EPITAXY

One of the advantages of this new compliant substrate technology is the potential to attain lateral control of semiconductor properties through strain-modulated epitaxy. When the substrate and epitaxial film share the strain elastically, this leads to the possibility to control the strain during the growth and, in turn, modify and control growth kinetics which depend on strain. By patterning the compliant substrate on the bottom, the growth kinetics can be modulated across the substrate, thereby laterally modulating such properties as the composition, thickness, and defect concentrations of semiconductors without any surface patterning. Modulating the growth kinetics by using strain in this manner is a new concept which could find a wide range of applications for new materials and devices. Since compliant substrates made using the epitaxial lift-off method can be processed on the top and the bottom, they are very well suited for this technology. A more detailed discussion of this concept will appear in another publication.

CONCLUSIONS

We have demonstrated a new compliant substrate technology based on high quality bonded thin film substrates. We have grown low composition $In_xGa_{1-x}As$ on these compliant substrates, both greater than and less than the conventional critical thickness. For $t > t_c$, we found that there is an inhibition of defect production on the compliant substrates compared to conventional substrates as observed by Nomarski microscopy and double crystal x-ray diffraction. For $t < t_c$, PL and the x-ray diffraction measurements showed that the samples were of excellent quality and uniformity. Since small compositional nonuniformity and large tilt prevented the determination of the role of the compliant substrate, experiments are under way to alleviate these factors. Experiments are also in progress on these samples and others in order to further quantify the nature of the compliant substrate-mechanical host bond and the role that it plays in defect production. We believe that this new compliant substrate technology is a viable approach that will find numerous applications to new material systems and devices. Strain-modulated epitaxy, one of the concepts that is enabled by this technology, has been introduced.

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REFERENCES

1. Y.H. Lo, *Appl. Phys. Lett.* 59, 2311 (1991).
2. A. Powell, F.K. LeGoues and S.S. Iyer, *Appl. Phys. Lett.* 64, 324 (1994).
3. Z. Yang, F. Guarin, I.W. Tao, W.I. Wang and S.S. Iyer, *J. Vac. Sci. Techol. B* 13 (2), 789 (1995).
4. J.P. Hirth and A.G. Evan *J. Appl. Phys.* 60 (7), 2372 (1986).
5. E. Yablonovich, T. Gmitter, J.P. Harbison and R. Bhatt, *Appl. Phys. Lett.* 51 2222 (1987).
6. G. Augustine, N.M. Jokerst and A. Rohatgi, *Appl. Phys. Lett.* 61, 1429 (1992).
7. See for example C. Camperi-Ginestet, M. Hargis, N.M. Jokerst and M. Allen, *IEEE Phot. Tech. Lett.* 3, 1123 (1991) and E.J. Twyford, J. Chen, N.M. Jokerst and N.F. Hartman, *45th Electronic Components and Technology Conf.* 770 (1995).
8. E. Yablonovich, E. Kapon, T.J. Gmitter, C.P. Yun and R. Bhat, *IEEE Photon. Tech. Lett.* 1 (2), 41 (1989).
9. G.L. Price and B.F. Usher, *SPIE: Physical Concepts of Materials for Novel Optoelectronic Device Applications I* 1361 (1990).
10. E. Yablonovich, D.M. Hwang, T.J. Gmitter, L.T. Florez and J.P. Harbison, *Appl. Phys. Lett.* 56 (24), 2419 (1990).
11. J.F. Klem, E.D. Jones, D.R. Myers and J.A. Lott, *J. Appl. Phys.* 66 (1), 459 (1989).
12. An $In_{0.04}Ga_{0.96}As$/GaAs quantum well with a thickness of 80 ML was grown on top of the 2000Å layer. This structure was very thin and did not affect the experiment.
13. H. Morkoç, B. Sverdlov and G.-B. Gao, *Proc. of IEEE.* 81 (4), 493 (1993).