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Integration of Diffractive Lenses with Addressable Vertical-Cavity Laser Arrays

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ABSTRACT

An optical interconnection system is being developed to provide vertical, digital data channels for stacked multichip modules. A key component of the system is an array of individually addressable vertical-cavity surface-emitting lasers with diffractive lenses integrated into the substrate to control beam divergence and direction. The lenses were fabricated by direct-write e-beam lithography and reactive ion beam etching into the GaAs substrate. Preliminary device performance data and the design and fabrication issues are discussed.

Keywords: diffractive optics, binary optics, vertical cavity lasers, semiconductor lasers, optical interconnects, multichip modules, e-beam lithography, fabrication of diffractive optical elements

1. INTRODUCTION

Vertical-Cavity Surface-Emitting lasers (VCSELs) are very attractive for a variety of integrated photonic system concepts. Two dimensional arrays are required to provide the compact geometry needed by many parallel optical interconnect systems[1]. However, without a discrete optical element such as a focusing lens, the diverging gaussian beam can introduce cross-talk if the adjacent receivers are within the spread of the beam diameter. In addition, the direction of the output beam limits many applications to on-axis system configurations. Integrating diffractive optical elements on the transparent substrate of a substrate-emitting VCSEL provides a method for controlling the direction and minimizing the divergence of the exiting beam[2]. We present the development of integrated, high-efficiency diffractive optics on an array of substrate-emitting VCSELs. Two types of diffractive optical elements have been fabricated so far; on-axis and off-axis lenses. These lenses are produced by etching the GaAs substrate to form the surface relief profiles needed for multiple phase-level diffractive lenses. The basic device concept is illustrated in Figure 1.

2. SYSTEM APPLICATION

A major motivation for this effort is the need for compact, two-dimensional arrays of surface-emitting sources with well controlled beam properties for optical interconnects in multichip modules[3]. Multichip modules (MCMs) are a high density, high speed electronic packaging technology that allows the mounting and interconnection of a number of bare integrated circuit die on a single substrate. Additional packaging density can be obtained by vertically stacking the modules. Routing signals from one vertical level to another then becomes important. We are working on a vertical photonic interconnect scheme based on two-dimensional emitting and receiving arrays that can be included in the MCM technology. VCSELs have very desirable attributes as source arrays, due to recent improvements in VCSEL device efficiencies and total power consumption for this type of application[4]. We have concentrated on 980 nm

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emitters, for which GaAs substrates are transparent, but MCM substrate materials (including silicon) are not transparent. This then requires that the MCM substrates incorporate via holes to transmit the optical signals. The size of the via holes are limited by the laser hole drilling process, the packing density desired for the emitter and receiver arrays, and the mechanical and thermal properties needed for the substrates after drilling. The current prototype design incorporates 100 micron diameter holes in a 650-micron thick silicon substrate . The design of the prototype demonstration of the vertical photonic interconnect is shown in figure 2. The total distance from the VCSEL substrate surface to the receiver substrate surface is 850 microns. The divergence of the VCSEL emitters is sufficiently large that large losses would occur in transmitting the beam through the via hole. A lens is needed to reduce the divergence of the beam and increase the efficiency of the transmission through the via hole. The receiver is a AlGaAs/InGaAs PIN photodiode and heterostructure bipolar transistor (HBT) on an InP substrate. In order to optimize the receiver for good high frequency response, the photodiode is made small (~50 microns). A collecting lens on the InP substrate also helps to improve the signal collection efficiency. The fabrication technology of the InP lens is currently being developed. This report is limited to the fabrication and performance of the integrated VCSEL-lens combination.

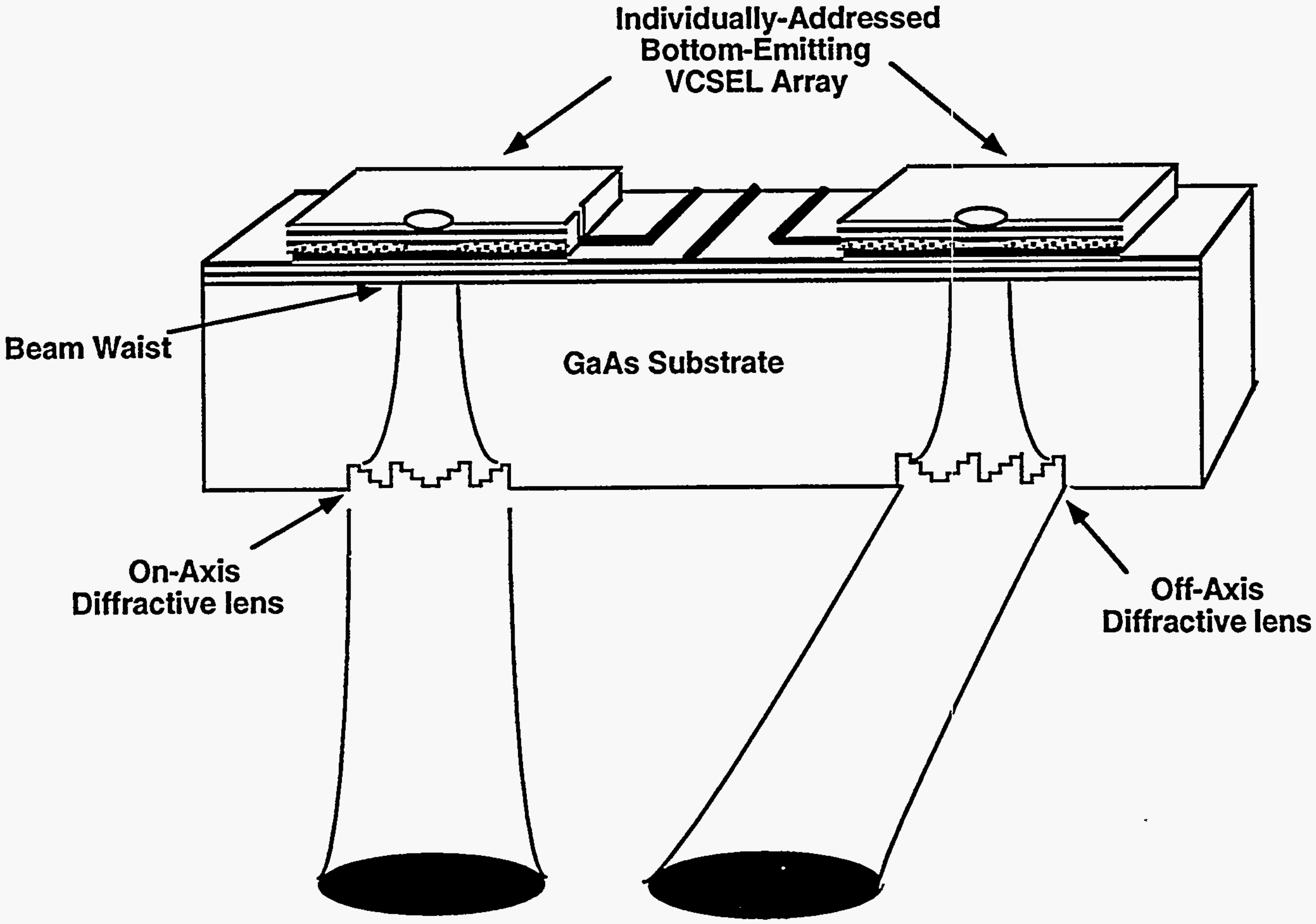

Figure1. Conceptual drawing of cross-section of part of an individually-addressable VCSEL array showing integrated diffractive lenses etched into the transparent substrate of the array.

It is important to note that the prototype depicted in figure 2 is not compatible with a specific MCM technology. The implementation of a MCM technology requires a consistent method of interconnecting the die on the same module. This electrical interconnection may be provided by a metallization on the MCM substrate that the die are bonded to or may be a separate interconnect structure that is bonded to the tops of the die.[5] In either case, it is impractical to mix the two mounting techniques in the same assembly as is shown in the prototype depicted in figure 2. A practical implementation of the vertical photonic interconnect will require more advanced optical routing concepts to be compatible with an existing MCM architecture. For example, bottom-emitting VCSEL arrays may be required with the light routed through the top of the device to maintain compatibility with an electrical interconnect to the tops of each die. Top-emitting VCSEL arrays may not be suitable because integration of a lens for divergence control directly on top of the emitter would not be practical. Such optical routing schemes provide motivation for investigating reflecting and off-axis optical elements.

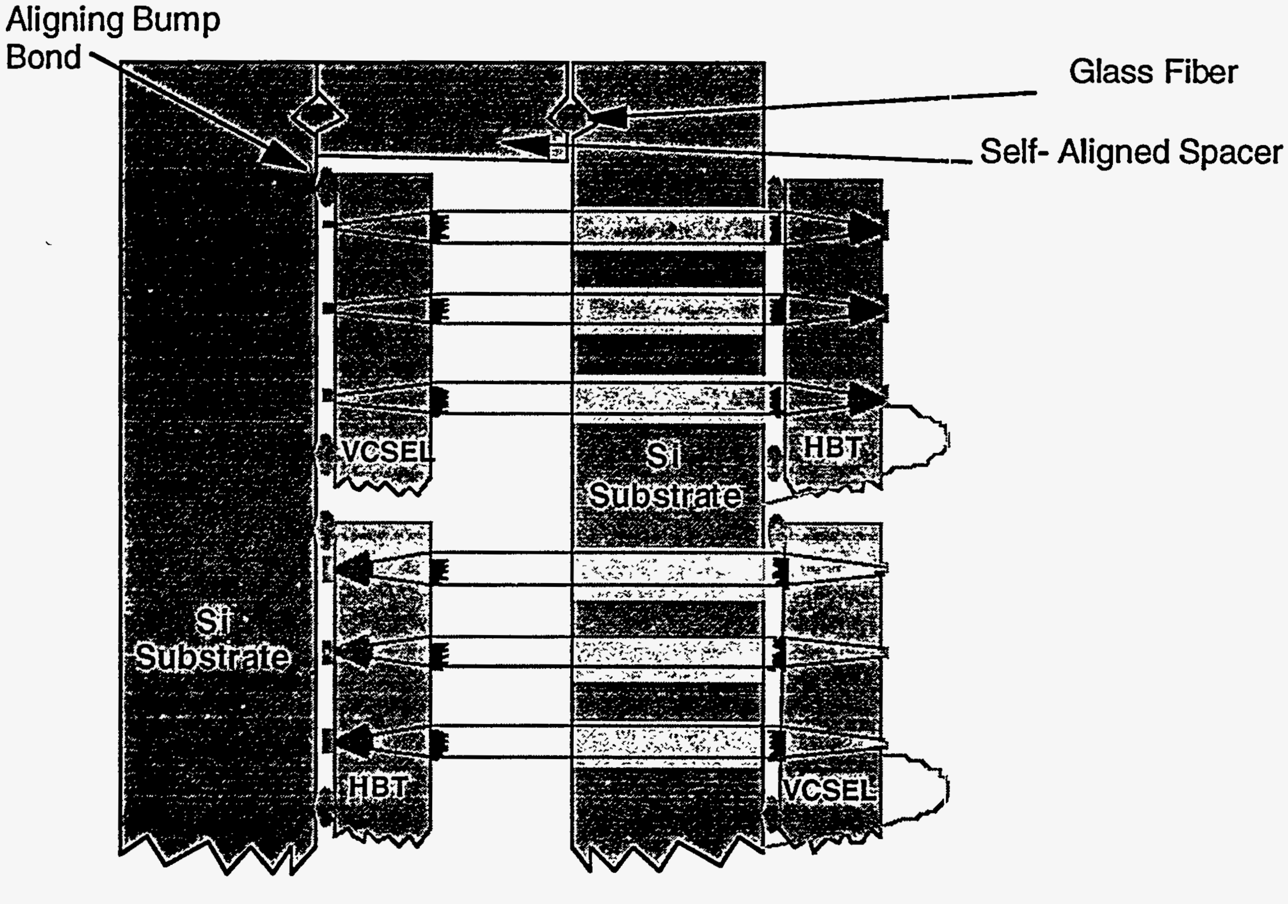

Figure 2. Depiction of prototype vertical photonic interconnect demonstration for MCMs. VCSEL emitter and HBT receiver modules with integrated diffractive lenses communicate through via holes in the MCM substrates.

3. VCSEL ARRAYS

The MOVPE-grown bottom-emitting VCSEL structures consist of a triple InGaAs quantum well active region with graded AlGaAs/GaAs DBR mirrors on top of the n+ GaAs substrate. The wafer growth technique and process steps involved to produce this device are similar to that reported elsewhere[4]. The VCSELs are fabricated for enhanced backside emission with an unannealed gold layer deposited over an aperture in the p contact metal aligned to the implant-defined active region. The VCSELs are currently mesa isolated devices with an active region defined by proton implantation. The active region diameters are 10, 15 and 20 microns. The design wavelength of the devices described here is nominally 980 nm. The VCSELs are fabricated as 4 X 4 arrays on 500 micron center-to-center spacings with top-side n and p contacts.

4. LENS DESIGN AND FABRICATION

The choice of lens parameters for the VCSEL arrays is based on the dimensions of the planned prototype depicted in figure 2. The lens was designed to produce the smallest spot size on the surface of the receiver substrate 850 microns away from the VCSEL substrate surface. The VCSEL substrate thickness was chosen to be 350 microns and the beam waist diameter of the VCSEL assumed to be 8 microns, based on divergence measurements of previous devices. It is necessary to consider the gaussian beam properties of the laser in designing the lens. Calculations of beam size at the receiver as a function of lens focal length were performed with ABCD matrix techniques. The on-axis lens design is 110 microns focal length with an 80-micron lens diameter. The $1/e^2$ beam diameter at the receiver substrate surface is predicted to be 60 microns. Note that the lens diameter is much larger than necessary as the beam diameter at the lens is predicted to be 18 microns for these design parameters. Small misalignments of the lens to the VCSEL are magnified by a factor of ten at the receiver plane. The misalignment tolerance of the lens to the VCSEL aperture is therefore approximately +/- 3 microns.

The VCSEL array is fabricated first on a substrate already thinned and polished to the desired thickness. The polished backside surface is protected during the VCSEL fabrication steps with a coating of SiN. The protective SiN coating is removed for the lens fabrication sequence and the wafer is mounted on a carrier substrate with the VCSEL side down for protection. The next step is to transfer the e-beam lithography alignment reference marks to the backside of the array from alignment features on the VCSEL side. This is done with a conventional contact mask aligner with an IR-sensitive CCD camera. IR light transmitted through the sample allows the photomask to be aligned to features on the laser side of the substrate. With care, this alignment can be held to one or two microns. A metal liftoff step then produces alignment features for the e-beam system on the substrate surface. The direct-write, e-beam exposure of the lens patterns is made in PMMA using a JEOL JBX-5FE electron beam pattern generator. After development of the pattern, the etching of the GaAs substrate is done in a chlorine reactive ion beam etch (RIBE) system. The RIBE system allows very anisotropic, uniform etching. The etch depths in GaAs are quite shallow and it is necessary to use an in situ monitoring technique to accurately stop at the correct depth. This is accomplished by optically monitoring the etch with a multilayer GaAs/AlGaAs semiconductor witness piece that is mounted beside the VCSEL sample. A laser beam reflected from the monitor is modulated as the layer structure is etched away and the modulation pattern can be calibrated to the actual etch depth in the GaAs sample. Three successive mask and etch processes are used in the well known "binary optics" process that results in an eight phase level lens.[6] The smallest linewidth in the on-axis lens patterns is approximately 0.3 microns. After completion of the lenses, the wafer can be unmounted for testing and packaging. A scanning electron micrograph of a finished lens is shown in figure 3.

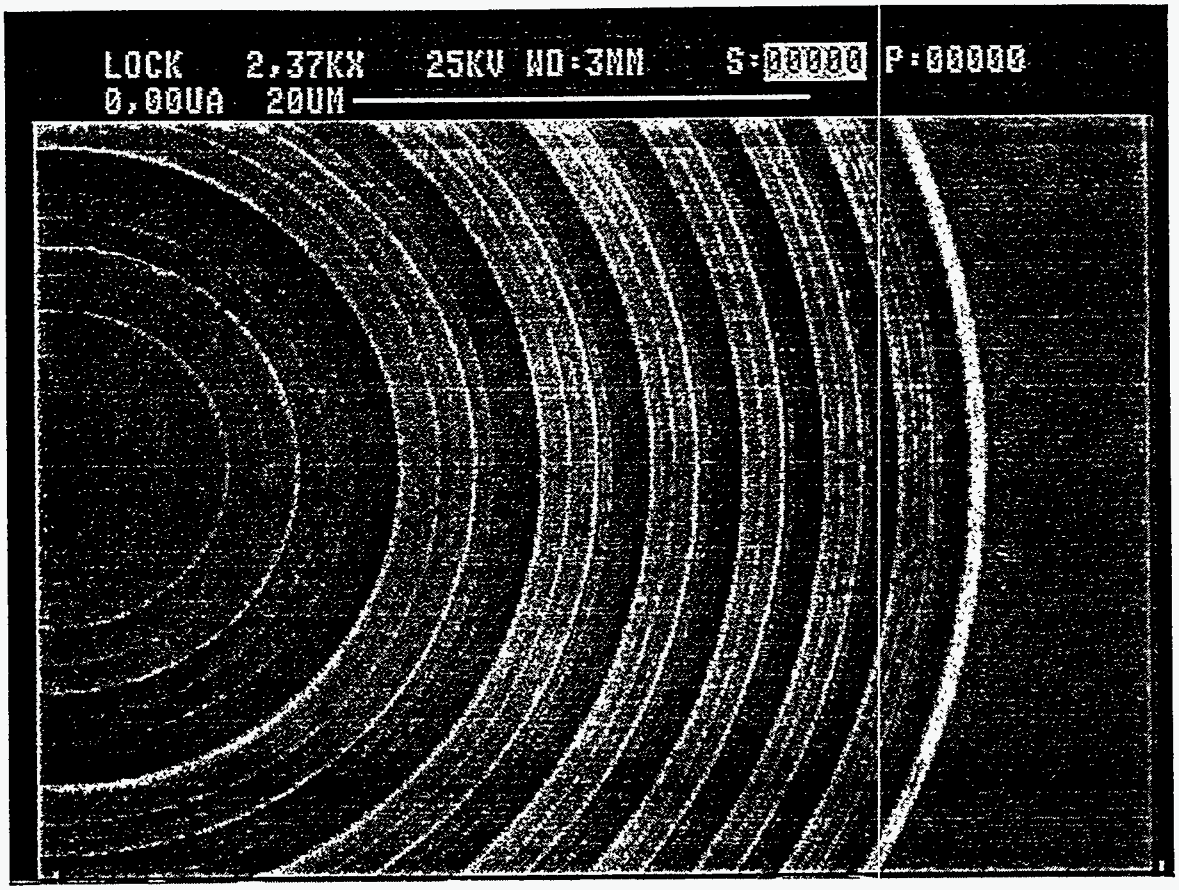

Figure 3. Scanning electron micrograph of the surface of a diffractive lens fabricated in GaAs. The 80 micron diameter lens has 8 phase levels in each zone.

5. DEVICE PERFORMANCE

We have measured preliminary characteristics for lenses fabricated on functioning VCSEL arrays. Figure 4 shows a direct before-and-after comparison of the light versus current (L-I) curves for a 20 micron diameter device taken without a lens on the substrate and then taken again after a diffractive lens was fabricated. Both devices had uncoated substrates. Fabry-Perot resonances due to the optical cavity formed by the substrate can be seen in both L-I curves. The data shows some degradation of the device efficiency after fabrication of the lens. This may be attributable to change in the amount and type of feedback into the laser from the back reflections from the substrate after the diffracting lens pattern is present. Another possible factor may the added thermal cycling of the device in the lens fabrication steps. The efficiency of power transmission through a 100 micron pinhole 850 microns from the lens was measured for devices with and without lenses. Figure 5 shows a comparison for a 15 micron diameter VCSEL without a lens and a 15 micron diameter VCSEL with a lens that is located nearby on the same substrate. The efficiency through the pinhole increases from about 20% without a lens to 80% with a lens. The decrease in the efficiency with increasing current for the device without a lens is attributable to the thermal lensing effect changing the laser's effective waist size and increasing the beam divergence. Because these devices had moderately high resistance, the thermal lensing effect is larger here than it may be in less resistive devices. These measurements have been made with CW operation of the lasers. Pulsed measurements, closer to the actual operating conditions of the interconnect system will be made soon.

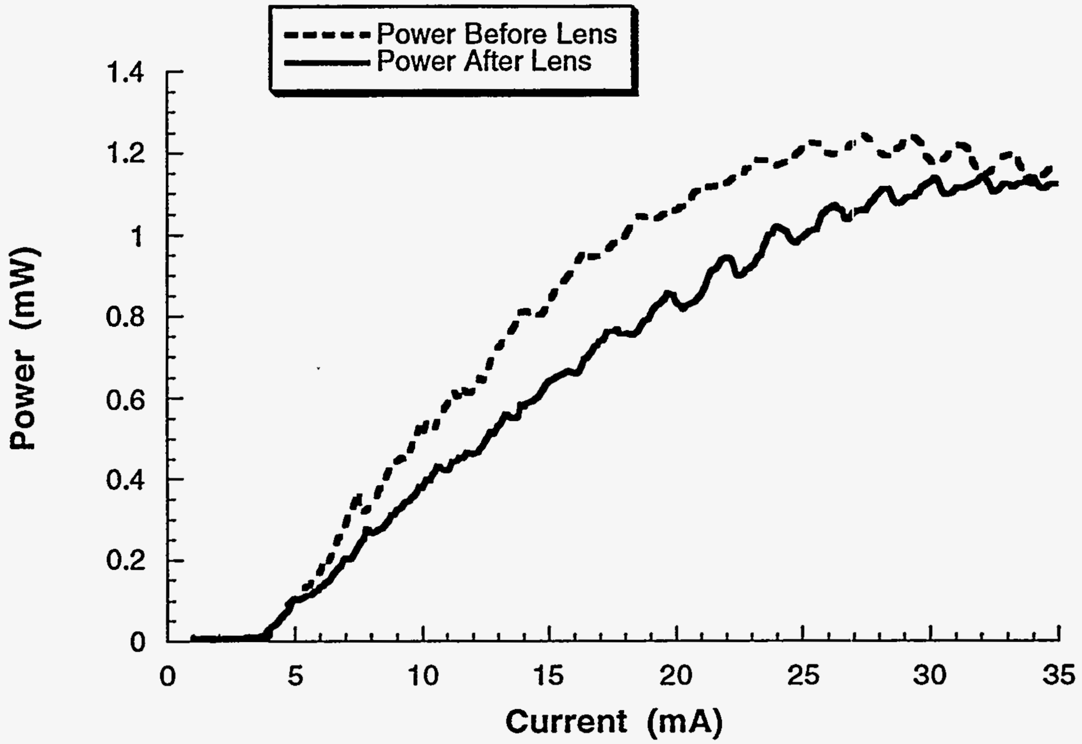

Figure 4. L-I curves for a 20-micron diameter VCSEL taken before and after fabrication of a diffractive lens on the substrate. Both curves were taken with an uncoated substrate. The ripples in the L-I curve are due to Fabry-Perot resonances in the substrate.

Devices with lenses show more asymmetrical structure in the beam profile at 850 microns from the lens than the unlensed VCSELs. This is presumably due to the less homogeneous feedback from the structured substrate surface affecting the transverse mode profile of the VCSEL. At higher currents, these VCSELs are operating with multiple transverse modes. We have not yet studied what effect this may have on random intensity noise (RIN) in the devices during pulsed operation and whether the feedback from the lenses will produce any additional noise.

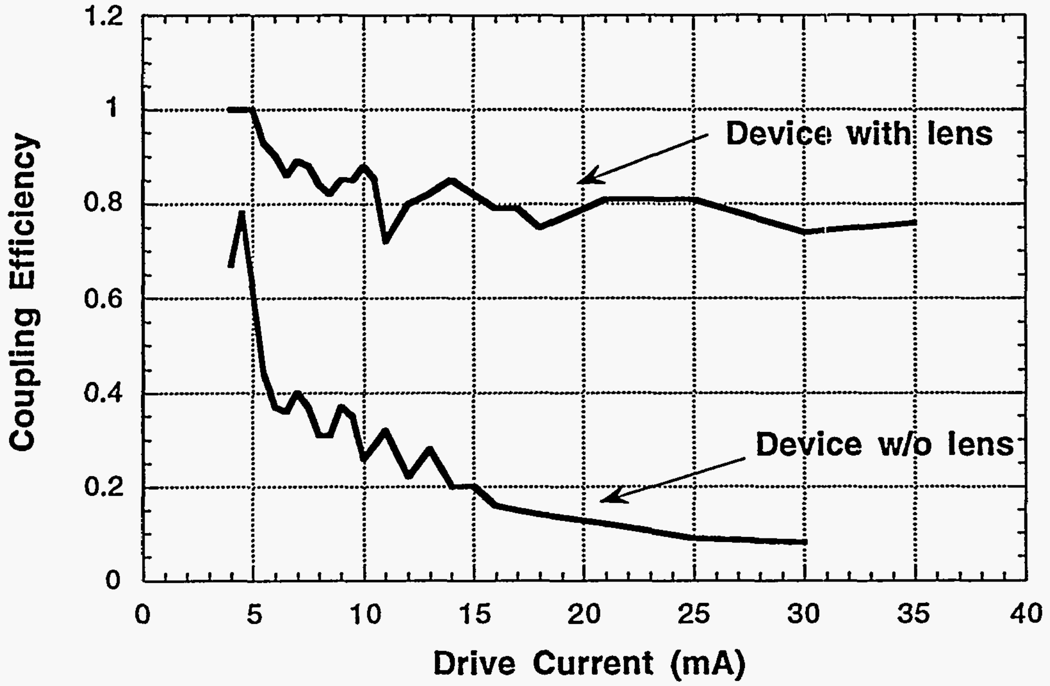

Figure 5. Comparison of coupling efficiency through a 100-micron pinhole located 850 microns away from the substrate surface for 15-micron diameter VCSELs with and without diffractive lenses on the substrate. The efficiency is plotted as a function of drive current.

6. OFF AXIS LENSES

Off-axis lenses were also fabricated on VCSEL substrates by the same process. The off-axis lens design was the same diameter and focal length as the on-axis lens with a 20 degree tilt for a collimated beam. The off-axis lens is effectively decentered in the aperture, resulting in smaller zone widths at one edge of the lens pattern. The minimum linewidth in the off-axis lens pattern is 0.17 microns. A scanning electron micrograph of an off-axis lens is shown in figure 6. Efficiency measurements through a 100-micron pinhole at 850 microns from the lens surface gave 75% coupling efficiency for a 15 micron diameter VCSEL. For this measurement it was necessary to align the pinhole and detector on the optical axis 20 degrees off from the normal to the VCSEL substrate. Integration of the off-axis lens demonstrates a capability to control the direction as well as the divergence of a VCSEL beam with integrated diffractive lenses.

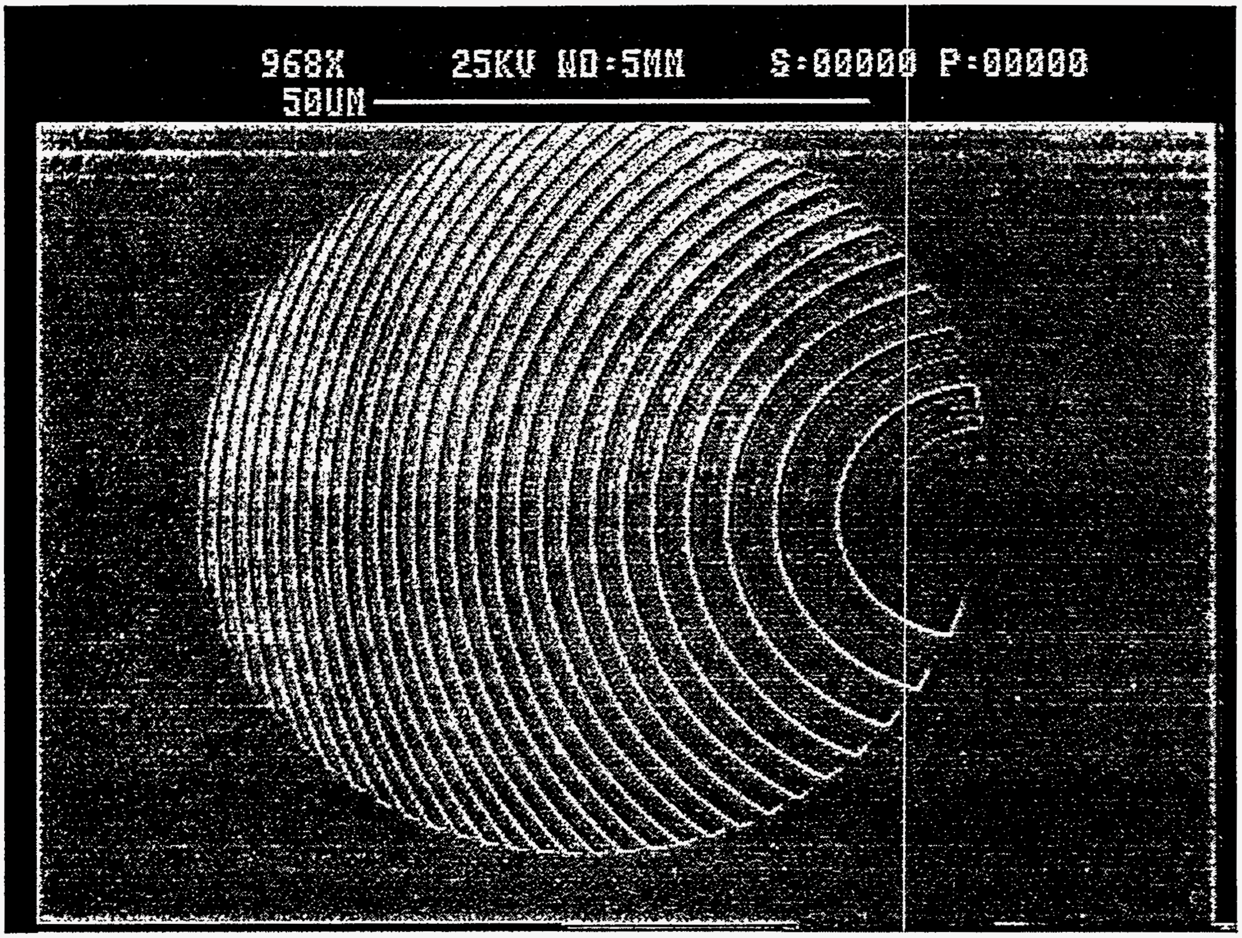

Figure 6. A scanning electron micrograph of an off-axis lens fabricated in GaAs. The 80 micron diameter lens has a focal length of 110 microns and is designed to produce a beam with an optical axis 20 degrees off from the normal to the substrate surface.

7. CONCLUSIONS

We have successfully demonstrated integration of multilevel, high efficiency, diffractive lenses with 16 element arrays of substrate-emitting VCSELs for optical interconnect applications. The lenses were fabricated by e-beam direct-write lithography and chlorine RIBE. Coupling efficiencies through a 100-micron pinhole located at the system receiver plane 850 microns from the lens surface were 80%. Advanced designs, such as off-axis lenses for directional control have also been demonstrated. We are currently planning to implement reflective elements and multiple lens designs as well. Feedback effects on the VCSELs from the diffractive lenses will be investigated and antireflection coatings evaluated for improved efficiency and feedback reduction.

8. ACKNOWLEDGMENTS

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