ENHANCED OPTICAL WAVEGUIDE FOCAL PLANE RESOLUTION UTILIZING A CHANNEL WAVEGUIDE FAN-OUT ARRAY COUPLED TO AN INTEGRATED CCD

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ABSTRACT

A channel waveguide array formed in a fan-out pattern and coupled to an integrated linear charge-coupled device (CCD) is presented as a means of enhancing optical waveguide focal plane resolution in integrated optical devices utilizing optical waveguide lenses. High spatial resolution can be obtained in this manner without making detector element spacings small, thus avoiding problems with regard to detector fabrication, cross talk, linearity and charge transfer efficiency. The channel waveguide array discussed herein has been fabricated using the lift-off process such that individual waveguide size is 5μm at the input end of the array tapering to a value of 25μm at the detector end of the array. Propagation of light from a HeNe laser in these channel waveguides has been demonstrated with a reasonably small amount of scattering observed. Low scattering is expected in view of the smooth channel waveguide surfaces apparent in scanning electron microscope pictures. The CCD portion of the device is a 4-phase device utilizing double level, overlapping polycrystalline silicon gate electrodes having a period of 32μm. A dual reset amplifier is incorporated at the CCD output. For these CCDs, transfer inefficiencies as low as 1.0×10^{-4} have been measured.

INTRODUCTION

The achievement of large time-bandwidth products utilizing the acousto-optic effect with surface elastic waves in planar optical waveguide structures (ref. 1) indicates considerable promise for the use of this effect for signal processing. The integrated optical spectrum analyzer (ref 2) utilizes this acousto-optic effect to perform Fourier transforms of signals in the 100-1000MHz range, with time bandwidth products on the order of 500 and frequency resolutions on the order of 1MHz appearing to be realistic. Inherent in the operation of the integrated optical spectrum analyzer are optical waveguide lenses (ref. 3-5) as the Fourier Transform of the electronic signal is determined by detecting the one-dimensional focal plane distribution of such a lens.

Constraints of limited substrate area and high frequency resolution lead to the use of small f-number waveguide lenses. To fully resolve focal plane light distributions for such lenses, detector arrays having center-to-center spacings of a few microns are required. As system requirements point toward several hundred resolvable spots, use of a CCD linear imaging array is advantageous. Forming a CCD linear image array having a period of several microns is difficult but possible. However, as integrated optical devices such as the spectrum analyzer are expected to use a semiconductor laser having λ = .82μm, the absorption length in silicon is about 15μm. (ref. 6) The fabrication of a CCD linear imaging array

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having a period significantly less than the absorption length, but in which channel isolation is to be maintained, adds considerable difficulty to the design and fabrication tasks. For these reasons we are presenting an alternate approach utilizing a channel waveguide fan-out array coupled to an integrated CCD. This device provides the desired fine spatial resolution, while allowing use of a CCD having a much larger period. The larger period simplifies CCD fabrication and provides improved channel isolation.

DEVICE CONFIGURATION AND PERFORMANCE

In linear CCD imaging arrays integrated into optical waveguide structures guided optical waves propagate along the wafer surface entering the imaging device laterally as opposed to entering from the front side or back side, as in conventional imaging devices. The optical channel waveguide fan-out array coupled to an integrated CCD differs from slab waveguide-CCD structures (ref. 7,8) in that the present structure is configured such that an individual channel waveguide is coupled to each array element of the CCD imager. The present device differs from previously-described channel waveguide arrays coupled to integrated CCDs (ref. 9), in that in the present device the channel waveguides are curved and tapered so that the waveguide center-to-center spacing is tapered from the CCD to a smaller value at the image plane.

The basic concept of the fan-out channel waveguide array coupled to a CCD is shown schematically in Fig. 1. The channel waveguides in this structure are formed by first utilizing anisotropic etching of the (100) silicon surface, then thermally oxidizing the surface to form a layer of SiO_2, and finally filling the V-grooves with a suitable liquid which serves as the waveguide medium. (ref. 10,11) Although channel waveguides can be formed by anisotropic etching as illustrated in Fig. 1, they can also be formed lithographically on the surface. We have used the latter approach in the present paper. In Fig. 1 each channel waveguide terminates at a detector element where the SiO_2 region gradually disappears in order to effect coupling of light from the waveguide to the detector element. (ref. 12) As light enters each detector element, carriers are excited and collected under each respective isolated section beneath the integration gate shown in Fig. 1. At the end of an integration time, the transfer gate is turned on so that the accumulated charge is transferred in parallel into the CCD. Once the transfer is accomplished the transfer gate is turned off and the charge packets are transferred along the CCD to the output where a multiplexed signal emerges. The procedure is then repeated.

The device shown in Fig. 1 has been fabricated with results shown in Fig. 2. Fig. 2-a shows a device with a V-groove channel waveguide array not formed in a fan-out pattern, while Fig. 2-b shows a device with a channel waveguide array formed lithographically into a fan-out pattern. The same CCD is used in both devices. This CCD is a 4-phase device utilizing two levels of overlapping polycrystalline silicon electrodes and incorporates an MOS output reset amplifier. Charge transfer inefficiency can be measured by serially injecting electrically a train of equal-amplitude pulses and noting degradation at the output. (ref. 13) A result of such measurements on the devices in Fig. 2 is shown in Fig. 3. Defining charge transfer inefficiency as the fraction of charge lost per transfer, the results in Fig. 3 correspond to a transfer inefficiency of

1.0×10^{-4}. Details concerning array isolation and uniformity for the device in Fig. 2-a have been presented elsewhere. (ref. 9)

The actual fan-out array pattern, shown in Fig. 1 and 2-b is computer generated. As each channel follows a sinusoidal path between the input and the output, the spacing between guides gradually increases. The sinusoidal path is a half cycle in length so that the slope is zero at each end. This is to insure a straight waveguide for best sampling at the input, and alignment ease at the output. The curved channel waveguides shown in Fig. 4 have been designed so that the curvature is small enough to avoid scattering due to waveguide curvature. (ref. 14)

A channel waveguide array incorporating a fan-out pattern has been fabricated utilizing polyurethane to form the waveguides. Since earlier channel waveguides have been formed by dripping polyurethane onto V-groove areas of integrated optical electronic devices after packaging and wire bonding, there was little or no control over polyurethane spreading, uniformity or thickness. Channel waveguides formed in this way were characterized by the serious problem of light leakage from channel waveguides into adjacent ones, since polyurethane also covered the area between V-grooves. A differential heating-lift off process discussed herein eliminates all these difficulties, and makes the V-groove formation optional, instead of essential to the creation of channel waveguide arrays. The process is thus applicable to substrate materials in which V-grooves cannot be formed. Using a positive photoresist, Shipley AZ1350J in this case, polyurethane pattern definition by lift-off seemed possible. The final differential-heating and lift-off process exploits the curing properties, as well as the lift-off process, to yield 5 micron resolution of repeatable patterns in polyurethane. Better resolution may be possible, but mask-making and photoresist processing limitations of our laboratory prevented us from trying smaller geometries. Details of this process will be published elsewhere. (ref. 14)

Fig. 4-a is a scanning electron microscope (SEM) picture of a typical device at the output end showing several channels, which are uniform in size, surface and edge quality. Fig. 4-b similarly shows the input end of the array. The spaces are very consistent and do extend down to the wafer surface. Some slight cross linking of channels does appear, but simultaneous exposure and development or preemphasis techniques, or just smaller waveguide duty cycles on the original mask would eliminate this.

For the device shown in Fig. 4 light propagation from the slab waveguide region into the high density end of the fan-out channel waveguide array is shown in Fig. 5. The curving of the light energy in the channel guides and the absence of excess scattering at the junction of the slab and fan-out channel waveguides demonstrate the high-resolution sampling of the optical image with a minimum of degradation due to scattering, and the transmission of this spatial information to the output ends where detection is possible. Cross talk measurements are currently in progress.

The use of a fan-out channel waveguide array for high resolution waveguide imaging could be extended to conventional imaging. Not only would the above advantages apply, but by controlling the waveguide refractive index by varying the waveguide composition, independent control of the image array modulation transfer function would be possible.

SUMMARY

Device configurations of an array of optical channel waveguides coupled to an integrated CCD have been presented. For applications involving a waveguide lens, we have configured the channel waveguide array into a fan-out pattern. Use of such an array circumvents the need to use a CCD with small element center-to-center spacing, thus alleviating problems with regard to line definition, CCD registration, and detector array crosstalk.

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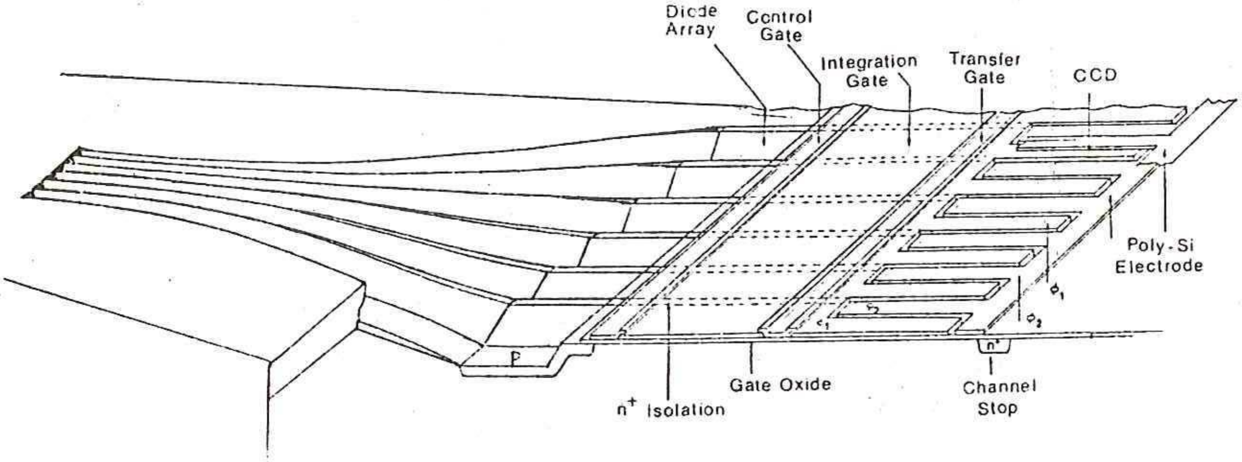
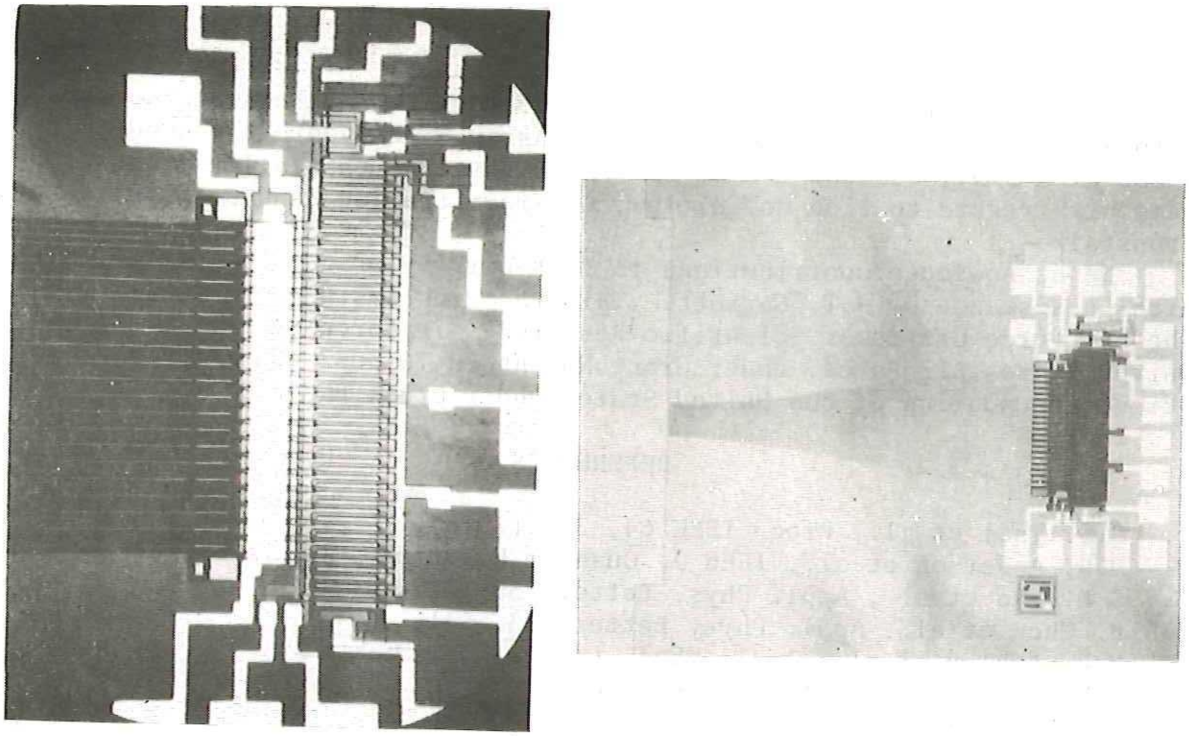


Fig. 1 Integrated CCD-Fan-out channel waveguide array device.



(a)

(b)

Fig. 2 (a) Device in Fig. 1 with V-groove channel waveguides not formed in a fan-out array, (b) device in Fig. 1 with planar channel waveguides formed in a fan-out pattern.

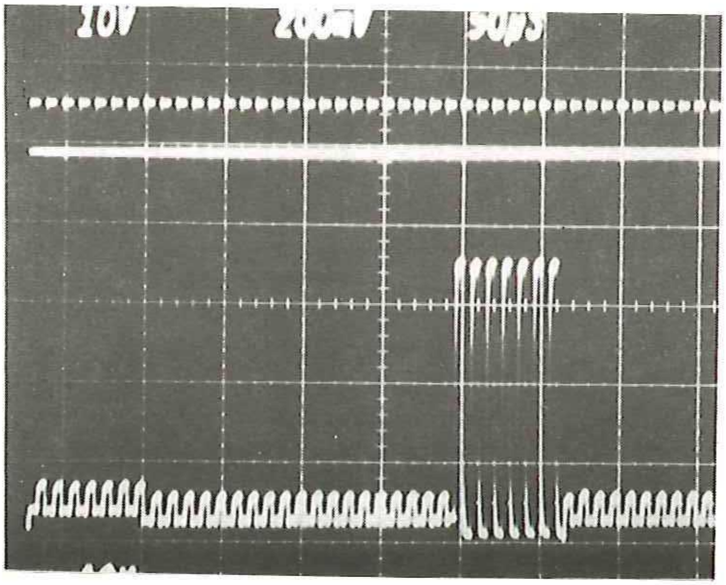
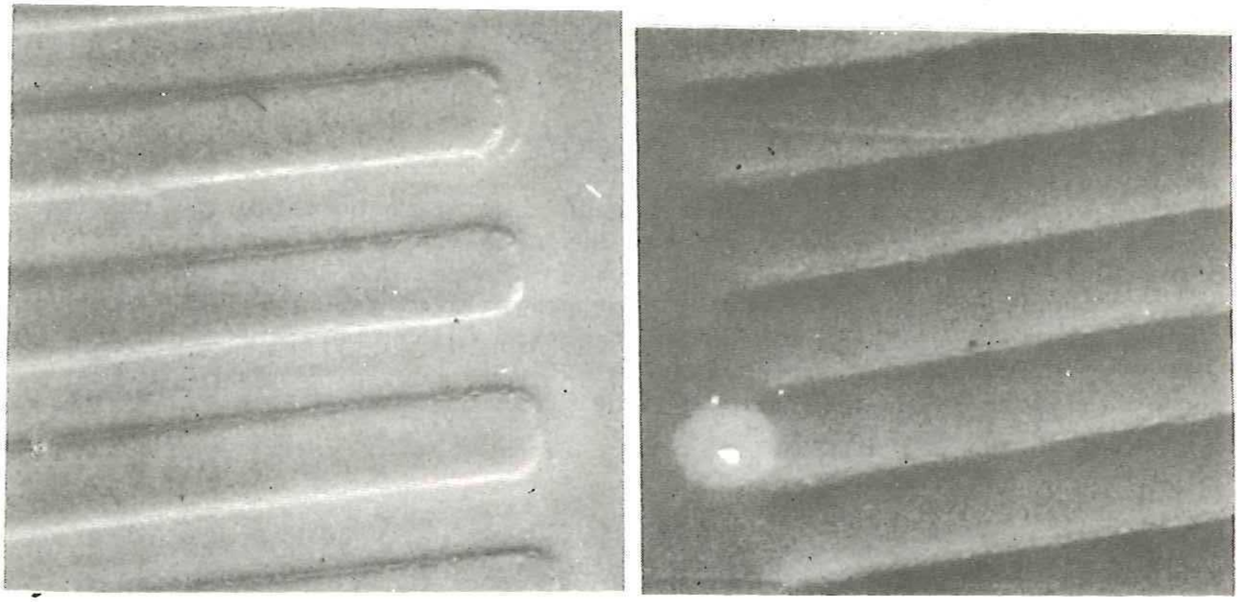


Fig. 3 CCD output corresponding to serial input of a group of equal-amplitude electrical pulses.



(a) (b)

Fig. 4 SEM picture of the ends of several channel waveguides at the (a) output end and (b) input end.

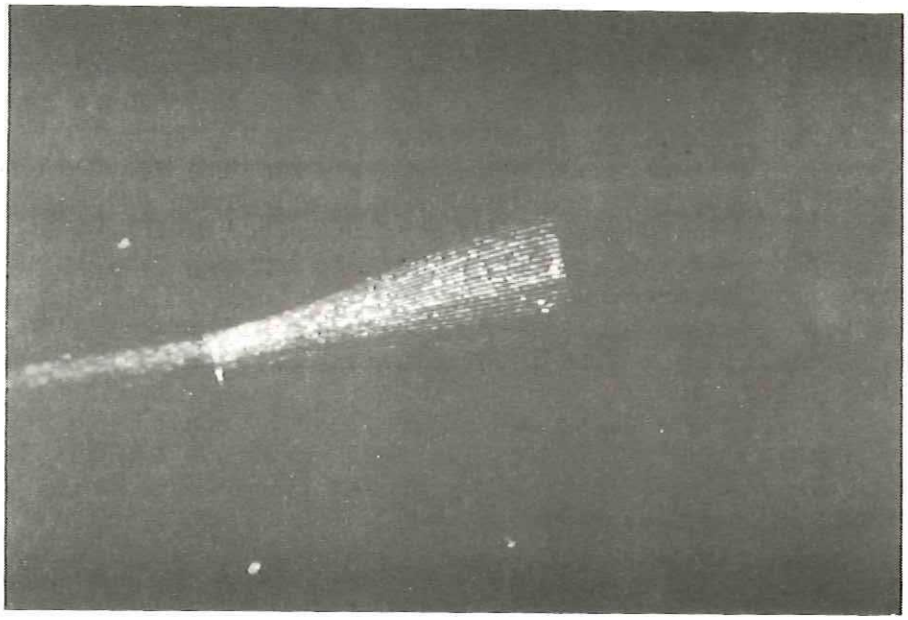


Fig. 5 Propagation of light from slab waveguide into the fan-out array of channel waveguides.