Optical Coupling of GaAs Photodetectors Integrated with Lithium Niobate Waveguides

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Abstract—**The optical coupling of GaAs photodetectors integrated with LiNbO$_3$ waveguides using epitaxial liftoff is measured and compared to calculations based on a complex index model. The measured coupling is found to be comparable to that obtained in epitaxial semiconductor waveguide detectors, but lower than expected. Low coupling efficiency is attributed to the presence of a low index barrier layer, not present in semiconductor-based structures, at the GaAs-LiNbO$_3$ interface. We propose a simple method to restore the coupling to its original value without the need to eliminate the barrier layer.**

LiNbO$_3$ is an important material for integrated optics because of its large electrooptic coefficients, low optical transmission and insertion losses, and the ease of waveguide fabrication. Semiconductor-based integrated optics is rapidly emerging as an alternative material system, in part because traditional semiconductor devices such as photodetectors and transistors can be integrated with the waveguides. The ability to integrate high-performance photodetectors with LiNbO$_3$ would open many new applications for the latter. We have recently reported the integration of single crystal GaAs metal-semiconductor-metal (MSM) photodetectors with LiNbO$_3$ as well as glass waveguides [1] using an epitaxial liftoff technique [2]. The technique involves selectively removing an epitaxial thin film of GaAs from the original substrate and transferring it to a new substrate where it is bonded by van der Waals forces. In this paper, we present a detailed analysis of the coupling of light from the LiNbO$_3$ waveguide to the lifted-off semiconductor photodetector.

With the large difference in the indexes of refraction between the two materials, we expect strong coupling of light from the waveguide to the photodetector. One measure of the strength of this coupling is the effective absorption coefficient α_{eff}, related to the imaginary part of the propagation constant, of a mode that is supported in the composite LiNbO$_3$-GaAs waveguide. The mode is lossless in the absence of the semiconductor, but it becomes lossy in the composite as the tail of the field distribution penetrates the semiconductor. In what follows, we show that the experimentally observed α_{eff}, as reported in [1], is lower than the value calculated from a complex-index model, study the origin of the discrepancy, and propose a simple method to offset the diminished coupling.

We lifted-off a 250 nm thick film of GaAs onto unannealed proton-exchanged planar LiNbO$_3$ waveguides and formed an array of detectors on the GaAs after the transfer. The detectors were 100 μm apart with each detector in the array consisting of a pair of metal stripes, separated by a 5 μm gap, running perpendicular to the direction of light propagation. With this geometry, the absorption coefficient α_{eff} can be deduced from the logarithm of the ratio of photocurrents measured on successive detectors; as long as the detectors have the same characteristics, the result does not depend on factors such as photodetector gain, surface recombination, and input coupling efficiency. With a planar waveguide, the light spreads laterally and averages the absorption over a large area.

We coupled ~0.5 mW HeNe laser light (λ = 632.8 nm) into the waveguide with a rutile prism and measured the photocurrent between successive pairs of metal stripes, the first of which was 150 μm from the leading edge of the GaAs. The waveguide without the semiconductor film supported two TM modes. Measured photocurrents of 6 and 4 μA at 5 V bias for the first two detectors yield an α_{eff} of 40 cm^{-1}. With this value of α_{eff}, calculated photocurrents of 2.7 and 1.8 μA were obtained for the detectors, in agreement with the data within the uncertainties introduced by the coupled laser power, the extent of the depletion region under the electrodes, and the detector gain. Furthermore, this suggests that the presence of any surface recombination at the bottom of the detector is not detrimental to its operation. Similar measurement for the TM$_1$ mode was not successful because the higher absorption of this mode, consistent with the results of calculations described below, greatly attenuated the light within the 150 μm long segment of GaAs before the first detector.

To estimate the expected α_{eff}, we calculate the complex propagation constants for this structure using a planar waveguide model. Implemented on a personal computer, the program can have an arbitrary number of layers with complex index of refraction and takes ~1 s to determine each propagation constant for the structures considered here. We use a complex index of $3.857 - i\,0.1978$ for GaAs at a wavelength of $\lambda = 0.6328$ μm [3], and real indexes of 1, 2.3, and 2.2 for the air upper cladding layer, the proton-exchanged guiding layer, and the unaltered LiNbO$_3$ lower cladding layer, respectively. The estimated thickness of the proton exchanged layer is 1.1 μm, which gives the two experimentally observed guided modes in the bare LiNbO$_3$. The mode of primary inter-

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est in the composite structure, which supports five TM modes (TM_0^c through TM_4^c), is the TM_3^c which has the largest overlap with the TM_0^L mode in the bare LiNbO$_3$ waveguide [4], [5] (superscripts *c* and *L* refer to the composite and LiNbO$_3$, respectively). Overlap integral calculations indicate that more than 98% of the power in the TM_0^L mode is converted to the TM_3^c. The calculated propagation constant for the TM_3^c mode yields an absorption coefficient of 760 cm^{-1} which is much larger than experiment and which cannot be accounted for by varying the model parameters within a physically reasonable range. To account for this discrepancy, we assume the existence of a low index barrier layer at the LiNbO$_3$-GaAs interface. The presence of such barrier would reduce the coupling through two main mechanisms: 1) the field evanescently decays in the barrier layer and is weaker in the semiconductor, and 2) the low index barrier screens the effect of the GaAs and enhances confinement of the mode in the LiNbO$_3$ until, for large barrier thickness, it resembles the TM_0^L mode.

The existence of a thin amorphous layer at the GaAs-LiNbO$_3$ interface has been verified from TEM analysis (Fig. 1). Although it is very tempting to interpret the width of the band in Fig. 1 as the thickness of an interfacial layer as viewed on a cross-sectional surface of the sample, this width actually represents a region where the electron transmission through the thinned specimen is significantly different from the surrounding regions. For this reason, the apparent thickness of about 10 nm may not be the actual thickness, particularly if the surfaces are rough on a microscopic scale. This apparent thickness varied across the TEM specimen and Fig. 1 shows one of the thinnest regions found. The exact composition of the layer is not well established at present, but we propose several possibilities that are consistent with the TEM observations. 1) A reasonable speculation is that it is closely related to the native oxide of GaAs whose refractive index is 1.65 [6]. Fig. 2 shows the calculated dependence of α_{eff} as a function of the oxide barrier layer thickness. The barrier thickness required to account for the observed α_{eff} is 40 nm, larger than is expected with our processing conditions and larger than suggested by the TEM micrograph. The oxide may be more porous and has an index considerably lower than 1.65, and therefore requires less thickness to account for the lower coupling. 2) A similar decrease in α_{eff} can also be obtained, as shown in Fig. 2, with either a 10 nm air gap or a combination of air with a 3 nm thick native oxide of GaAs. The presence of air is also a reasonable possibility since the surfaces of GaAs and LiNbO$_3$ are not atomically smooth. The GaAs layer, thus, may not perfectly conform to the topography and adheres only to the peaks leaving air spaces over valleys to give an average gap of 10 nm. In this scale of dimensions, the polished surface of LiNbO$_3$, typically obtained by a final mechanical polish using 100 nm grit, presents a surface roughness which is adequate for low-loss propagation but too great to ensure intimate contact with the semiconductor layer. 3) Another possibility is that the layer is composed of impurities, most likely organics, introduced during the liftoff process. A 20 nm layer with a refractive index of 1.3, typical of hydrocarbons, is sufficient to account for the decrease in coupling. A layer of this thickness can be consistent with the TEM micrograph as discussed above.

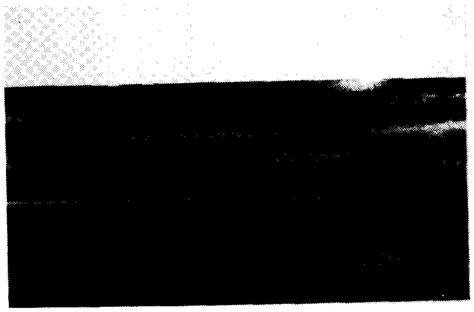

Fig. 1. Transmission electron micrograph of the GaAs-LiNbO$_3$ interface. The 250 nm thick GaAs is on top and the LiNbO$_3$ substrate is on the bottom. A thin, amorphous interfacial layer is sandwiched between them.

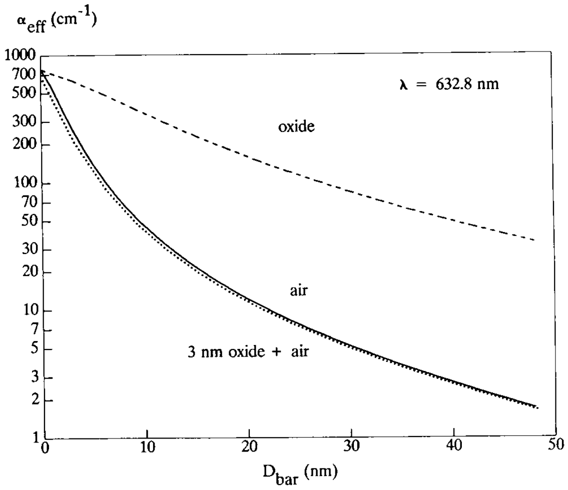

Fig. 2. Calculated α_{eff} for the composite mode that has the largest overlap with the TM$_0$ mode of bare LiNbO$_3$ at $\lambda = 632.8$ nm. The waveguide structure consists of air upper clad, 0.25 μm thick GaAs with $n = 3.857 - i0.1978$, D_{bar} barrier layer thickness, 1.1 μm thick proton-exchanged LiNbO$_3$ with $n = 2.3$ and LiNbO$_3$ lower clad with $n = 2.2$. Barrier layers considered are the oxide of GaAs with $n = 1.65$ (dashed curve), air with $n = 1$ (solid curve), and 3 nm of oxide and air (dotted curve).

Whichever the barrier layer composition turns out to be, the deposition of a thin enhancement layer between the LiNbO$_3$ waveguide and the GaAs can reduce, or eliminate altogether, the deleterious effect of the barrier layer even in the presence of such a barrier layer between the enhancement layer and the semiconductor. As discussed above, the coupling through the barrier layer decreases either by the decay of the field across that layer or by the increased confinement of the mode in the guiding layer. An estimate of the evanescent decay in the optical power through the barrier layer, given by $e^{-4\pi(n_{\text{eff}}-n_{\text{bar}})D_{\text{bar}}/\lambda}$ where n_{eff} is the real part of the effective index for the TM_3^c mode, n_{bar} is the index of the barrier layer, D_{bar} is its thickness, and λ is the free-space wavelength, yields only about a 25% decrease in coupling. The second mechanism is therefore dominant, and the main effect of the barrier is to force the mode deeper into the LiNbO$_3$ guiding layer.

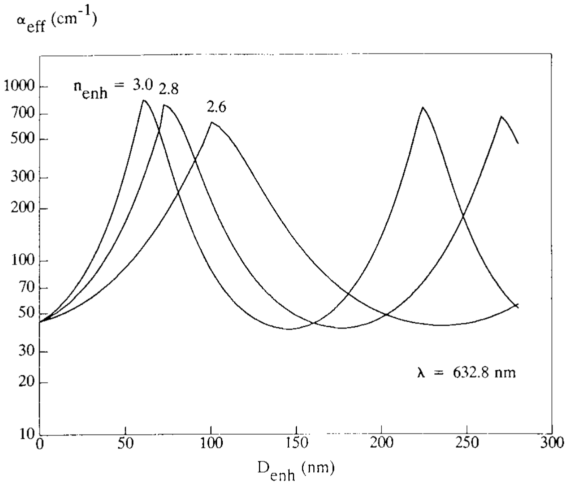

Fig. 3. Calculated α_{eff} showing the effect of an enhancement layer whose index n_{enh} and thickness D_{enh} are varied while in the presence of a 10 nm thick barrier layer with n = 1. The enhancement layer is between the LiNbO$_3$ guiding layer and the barrier layer. All other parameters are the same as in Fig. 2.

In order to improve the coupling, a layer with a higher index than the guiding layer and in intimate contact with it can be deposited to increase the field at the new detector–waveguide interface. Fig. 3 shows α_{eff} as a function of enhancement layer thickness D_{enh} with the enhancement layer index n_{enh} as a parameter while in the presence of a 10 nm thick air barrier between the GaAs and enhancement layer. It can be observed that α_{eff} has a resonant behavior and that it can be restored to almost its original value of approximately 760 cm^{-1} over a reasonable range of D_{enh}. Resonant peaks occur whenever a mode in the LiNbO$_3$-enhancement layer–barrier layer substructure cuts in, becomes phase-matched to the TM$_0^L$ mode and resonantly couples to the LiNbO$_3$ waveguide substructure. Away from these resonances, α_{eff} is restored to a lesser degree because of the weaker coupling between these two substructures.

Other methods of increasing the coupling, applicable with or without the barrier, involve decreasing the guiding layer thickness or increasing the substrate-guiding layer index difference [4], [5]. Altering waveguide parameters, however, is not always technologically feasible nor is it always desirable because they can affect device performance in other ways, such as in the insertion loss. Moreover, unlike the inclusion of the enhancement layer, they do not restore the degradation in coupling due to the barrier and may therefore be considered only as complementary methods.

In summary, we have analyzed LiNbO$_3$ waveguides integrated with lifted-off semiconductor photodetectors. The light couples from the LiNbO$_3$ waveguide to the GaAs detector to give an effective absorption coefficient α_{eff} of 40 cm^{-1}, a figure that is comparable to those obtained in all-semiconductor waveguide detectors [7], [8] but is still lower than calculated. The discrepancy in α_{eff} is attributed to the presence of a low index optical barrier layer at the waveguide–detector interface. Our calculations show that the deleterious effect of this layer can be offset by depositing a high index layer on the LiNbO$_3$ waveguide before the semiconductor is transferred onto it. Such a high index layer can restore the coupling to almost its original value without the need to eliminate the barrier layer.

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