A modular fabrication process for thin-film lithium niobate modulators with silicon photonics

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Abstract

We report advancements in the fabrication of electro-optic Mach-Zehnder modulators made by bonding an unetched thin film of lithium niobate (LN) to a second chip with rib waveguides in another material, such as silicon. Devices were fabricated after storing bonded silicon-LN chips in a common laboratory environment for more than three years. The chips survived the full processing flow and yielded modulators with greater than 50 GHz 3 dB electro-optic bandwidth, and $V_{π} L$ less than 3 V cm at 1550 nm and equivalent performance to freshly-bonded and processed chips. Furthermore, we demonstrate the co-integration of hybrid bonded thin-film LN modulators and silicon photonics based high quality-factor ring resonators and higher-order coupled microring optical filters. The silicon microring resonators are used for photon-pair generation at 1550 nm using spontaneous four-wave mixing. These results show the feasibility of a modular modulator fabrication procedure, where the planarization and bonding steps are performed for a batch of chips at one time and smaller sub-batches are customized by end users at a much later time according to their needs and convenience.

1. Introduction

Electro-optic modulation is a key functionality for both classical and quantum photonics, and has widespread applications in communications, switching, radio frequency (RF) waveform generation and pulse shaping [1–6]. For example, applications in quantum photonics where integrated high-bandwidth electro-optic modulators (EOMs) can be helpful are: time-to-frequency conversion in large-alphabet quantum key distribution where a phase modulator follows a dispersive element [7], and applying a time-dependent phase-shift to photons based on the measurement result of a prior stage [8]. In both cases, the 3 dB electro-optic modulation bandwidth should exceed the bandwidth of the filtered photons, which is typically around 50 GHz if standard telecommunications-grade optical filters at 1550 nm are used in the experiment [9]. The increasing demand for high-bandwidth operation by a diverse set of end users requires high performance EOMs to be designed and fabricated on a scalable integrated platform. However, we believe that not all the fabrication steps must be performed by each end user, and a modular design and fabrication approach may be highly attractive to small-volume users with demanding performance requirements, such as those in RF photonics and quantum photonics. We show such a roadmap using thin-film lithium niobate (LN) EOM devices designed and made without etching or patterning the LN thin film, co-integrated on a silicon photonics platform.

LN based integrated photonics have been widely used in classical and quantum photonics [10, 11]. Recently thin-film LN photonics has been a very active area of research with higher index contrast, more compact device footprints and greater modulation bandwidth compared to traditional LN EOM devices.
In order to achieve high-index contrast LN waveguides, various deposition methods have been explored such as, chemical-vapor-deposition [14], sol–gel [15] and sputtering [16], to produce thin-film LN on low refractive index substrate. However, the lattice mismatch between LN and substrate can result in poor crystalline film quality. A crystal-ion-slicing technique combined with direct wafer bonding [17–19] and chemical-mechanical-polishing (CMP) has led to the development of thin-film LN or LN-on-insulator (LNOI), which preserves many of the properties of LN crystals [20, 21]. Waveguide operation in the LNOI platform requires additional processing such as etching [22], rib-loading [23–25], bonding to photonic circuits [26], or a combination of these processes [27]. These processing developments have helped realize EOMs which improve upon bulk LN based EOMs [22, 26] and provides a platform for the scalable integration of other components such as filters [28], detectors [29] and lasers [30–32] for which silicon-on-insulator (SOI) technology is becoming popular.

Silicon (Si) wafers can usually be processed in a CMOS-compatible foundry using large (200 mm or 300 mm diameter) wafers. However, LN is not a CMOS-compatible material and thin-film LN is not available in large wafer sizes. Bonding of thin-film LN to patterned Si or silicon nitride (Si$_3$N$_4$) waveguides offers a site-specific, modular, and scalable approach for realizing hybrid photonic circuits. Our integration process requires minimal processing of the EO material and provides additional optical functionality by integration with a mature Si photonics process [26, 33, 34]. A truly modular process that benefits small-volume end users would enable most of the critical steps that require the highest precision and sophistication to be performed at the foundry level, perhaps leveraging a multi-project wafer for cost reduction, and then the wafers can be diced into smaller sections and distributed to end users for final-stage customization (typically, electrode design and end facet polishing, etc.). Perhaps a significant time interval may pass between the first stage of fabrication and the final stages if the end users do not process a high volume of chips at once. For bonded waveguides, a question may arise about the long-term stability of bonded but unfinished samples. Here, we demonstrate that both the optical and microwave properties are preserved for shelved versus fresh samples. We demonstrate a modular design and fabrication approach and show that pre-bonded Si-LN chips stored at room temperature for an extended period (3 years), can withstand post-fabrication processing and thermal cycles (up to 270 °C), while preserving the properties of the device.

2. MZI design

The Mach–Zehnder interferometer (MZI) is a widely used structure in implementing quasi-unitary gate operations, path switching, amplitude modulation, filtering, analog computing and simulation, and other photonic signal processing functionalities that are important in both quantum and classical regimes. An MZI structure splits classical input light equally into two waveguide arms, and presents one of two possible propagation paths for single photons. The couplers can be implemented using either multi-mode-interference waveguide splitter or a waveguide directional coupler (DC). Light propagating in each arm experiences a user-controlled phase-shift, typically between 0 and π/2 radians. This phase-shift can be converted into intensity modulation, for example, by recombining the two waveguide arms. Alternatively, the output port taken by single photons can also be controlled using the phase-shift. Large-scale arrays of such devices can be made using integrated photonics [35].

Our canonical MZM structure consists of unbonded silicon photonic waveguides and a hybrid-bonded LN phase-shifter section, as shown in figure 1(a). The Si waveguides (in both the bonded and unbonded regions) are designed for TE-polarized guided fundamental modes of light around 1550 nm. The Si photonic waveguides outside the bonded region include the edge couplers, 3-dB adiabatic DCs, and path-length difference segments (PLD). If used, a PLD section should precede the phase-shifter section, as shown in figure 1(a) which indicates left-to-right optical and microwave signal propagation. At the unbonded-to-bonded interface, the Si waveguide width is kept wider than 600 nm to confine more light inside the Si rib waveguide. This ensures minimal optical loss (estimated to be around 0.1 dB) due to the modal-mismatch and the scattering loss from the LN edges. Once the guided mode is under LN, the strength of modulation depends on the interaction of light within the LN layer. Adiabatic waveguide tapers are used for vertical inter-layer transitions of the TE-polarized mode from Si to a hybrid LN mode (and vice versa). The hybrid waveguide design [26] allows 81% of the guided light (calculated using the spatial integral of the Poynting vector) inside the bonded unetched-LN layer with a simulated effective mode area of 1.5 $\mu$m$^2$. Only about 5% of light resides in the narrow Si waveguide and the rest of the light is in oxide. Etched LN waveguides also have a certain fraction of the light in oxide (the cladding) and outside of the LN core.

For high RF bandwidth modulation, it is important to match the velocity of the RF and optical waves, achieve a low RF loss, and match the source, transmission line and load impedances [36, 37]. The microwave velocity, impedance and loss are frequency-dependent parameters of the RF-transmission line characteristics which are determined by the dimensions and materials composition of the dielectric stack and the electrode...
geometry (see figure 1(b)) [38]. A coplanar waveguide (CPW) travelling-wave electrode design was used to match the RF phase refractive index and the optical group refractive index. In the case of two specific devices [Group I and Group II (see table 1)] that were measured, the CPW’s were designed in a push-pull configuration with an electrode gap of 8 and 9 μm between signal (S) and ground (G), signal width of 34 and 55 μm, and 0.75 μm thickness of the gold layer. Note that the gold thickness is significantly less than in traditional LN high-speed modulators [36] and is therefore easier to fabricate. Using a finite element method solver, the simulated microwave characteristic impedances of the Group I and Group II CPW designs were calculated to be 42 Ω and 52 Ω at 50 GHz, respectively.

3. Hybrid fabrication

Some approaches to bonding thin-film LN to SOI chips used benzocyclobutene (BCB) assisted bonding [39]. Among the many methods of testing bonding strength, mainly focused on materials science, is the ability to withstand the processing steps required in device fabrication [40]. Although BCB offers robust and good bonding strength, the stability and reliability concerns with BCB have been mentioned in literature [22, 41–44]. Besides the poor thermal conductivity (0.29 W m⁻¹ K⁻¹) which may affect the device performance [32], delamination of the bond interface has also been observed when BCB is exposed to harsh chemical or thermal cycles (greater than 300 °C) [39]. This may impact the bond reliability during back-end fabrication processes [43].

Our fabrication approach involves direct bonding of unpatterned x-cut thin-film LN on Si photonics-based rib waveguide features. Optical mode confinement is provided by the features only etched in the Si photonics layers and no etching of the LN layer is required [45]. LN facets oriented normal to the crystal plane (i.e. along the z-axis) are not exposed near the optical mode, since the LN film is essentially a wide and thin slab, which is loaded by a Si rib. The Si waveguide features were fabricated using deep ultraviolet (DUV) photolithography on 200 mm diameter SOI wafers with 150 nm thick Si and 3 μm thick silicon dioxide (SiO₂). The wafer handle consists of high-resistivity Si, which is necessary for high-bandwidth EOMs. After patterning the Si layer, SiO₂ was deposited using a high-density plasma process, and surface planarization was performed to a thickness of about 40–100 nm above the Si layer using a CMP process on the whole 200 mm wafer. Wafer-scale CMP typically yields better and more repeatable results than CMP on individual dies that are about 1 cm² in size. Separately, thin-film LN (or LNOI) wafers with 600 nm x-cut LN thickness and 2 μm buried SiO₂ thickness were commercially procured (NanoLN, Jinan Jingzheng Electronics Co., Ltd). The handle of this wafer was normal Si, whose resistivity is unimportant since it will be removed as part of the subsequent bonding process.

As shown in figure 2(a), a direct bonding procedure was implemented by a sequence of steps that involve chip cleaning, surface plasma activation, and pre-bonding (which is essentially a temporary bond performed at room temperature) followed by elevated temperature annealing under pressure, which strengthens the bond. A similar process was described in our earlier work [26]. The SOI and LNOI wafers were diced, and the individual dies were thoroughly cleaned in RCA-1 (1:1:5 ratios of NH₄OH, H₂O₂ and H₂O) to remove dust particles and contaminants. If the surfaces to be bonded are not adequately clean, unbonded voids can occur and can cause bonding to fail. Just before bonding, plasma surface activation (PSA) of the surfaces was achieved using an oxygen-based RF-plasma treatment at 150 W and 1.103 mbar, for 180 seconds. The plasma treatment makes the surface highly hydrophilic, which enables direct bonding of heterogeneous surfaces at low temperature [46–52]. After the PSA, the dies were soaked for 10 minutes in deionized (DI) water and blow-dried using a nitrogen gun. The dies were then bonded by bringing the surfaces into contact at room temperature. The bonded-interface is initially held together upon contact by relatively weak Van der Waals
forces, and slight pressure applied to the chips leads to the spreading of the bonding over the whole contact area. Subsequently, the bonded sample was annealed with elevated temperature cycles (200 °C for 1 h, 250 °C for 1 h, and 300 °C for 2 h) [46, 50, 53] under an applied pressure of about 9.8 N cm⁻². Slow heating and cooling rates were used to minimize the pyroelectric field buildup, if any. The preceding processing steps can be performed on a large batch of chips in parallel, and the bonded samples can be stored for later processing. Some of the samples processed as described in this paragraph were stored on a shelf in our common laboratory environment for more than 3 years; we label this batch of chips ‘Group I’. A second group of chips, labeled ‘Group II’, were processed using the same steps but all at one time, without the intermediate storage. Previous studies have shown that long storage at room temperature of plasma activated bonded samples causes rearrangement of water molecules, to form covalent bonds which improves the bond strength [48, 50]. However, high temperature anneal can result in debonding due to mismatch of thermal expansion coefficient [54]. In our work, we did not observe any debonding when the bonded samples (both Group I and Group II) were annealed with temperature cycles up to 270 °C.

For both Group I and Group II chips, the samples were cleaned using a piranha solution (3:1 ratio of H₂SO₄ and H₂O₂). Plasma-enhanced-chemical-vapor-deposition (PECVD) was used to deposit 2 µm thick SiO₂ at 270 °C. This step is needed to deposit an oxide cladding layer for the waveguides outside the bonded region (which otherwise only have about 40 to 100 nm of oxide above the Si waveguide core layer). The next step is to remove the handle and oxide layers above the bonded LN. The bonded sample was coated with a protective temporary wafer bond polymer to prevent etching of SiO₂ and Si where not desired. The PECVD SiO₂ on top of LNOI was etched using 49% hydrofluoric (HF) acid to access the top LNOI Si handle. Then, the LNOI Si handle was selectively removed by using a timed XeF₂ isotropic dry etch, and the remaining buried oxide layer was removed using a quick immersion in a hydrogen fluoride solution. Next, the protective polymer was removed by a solvent-based cleaning step. The traveling-wave electrode designs were patterned on a negative photoresist using a direct-laser writer. An e-beam evaporator was used to deposit titanium and gold of thicknesses 20 nm and 750 nm, respectively, followed by a lift-off process to complete the fabrication of the electrodes. As shown in figure 2(b), the ground-signal-ground (GSG) electrode design includes flare-outs at the ends to facilitate device probing using standard RF GSG probe tips. Figure 2(b) shows optical microscope images of such a travelling-wave electrode structure which was fabricated on top of a thin-film of x-cut LN, bonded to a planarized chip containing Si rib waveguides.
4. Measurements

The optical transmission was measured using a tunable laser (Agilent, 81 640A) and a photodetector (Agilent, 81 634B). Light from a tunable laser source was coupled in and out of the chip using polarization-maintaining lensed tapered fibers (PMF) and the transmission was measured from 1520 nm to 1570 nm as shown in figure 3(a). The measured MZM was an asymmetric push-pull modulator with a path length difference between the arms, resulting in a measured free spectral range (FSR) of 6.2 nm and an extinction ratio (ER) of 29.4 dB. The end-to-end insertion losses of the Group I and II MZMs were 14.7 and 12.2 dB, respectively. These insertion losses are primarily due to the fiber-to-chip coupling loss (5.3 dB per facet), which can be further improved by using a more optimized edge coupling design. After characterizing the transmission curve of the MZM, the laser wavelength was fixed at the quadrature-point, and the value of $V_\pi$ was measured by applying trapezoidal waveforms using a pulse pattern generator (PPG), as depicted in figure 3(b). Trapezoidal waveforms are similar to triangular waveforms used in other reports [55, 56], but also allow the slew rate and level-hold times to be adjusted independently for further detailed studies of bias drift and stability, to be reported elsewhere. The modulated optical waveform was amplified using an erbium-doped-fiber-amplifier (EDFA) and detected using a photodetector with an integrated trans-impedance-amplifier (TIA). The electrical output of the TIA was captured using an oscilloscope.

Figure 3(c) shows the driving electrical signal (blue) and the modulated optical signal (orange) at 1 MHz. The peak-to-peak voltage of the trapezoidal waveform is set higher than the expected $V_\pi$ of the modulator, ($V_{pp} = 10$ V in figure 3(c)). This causes overshoots in the measured optical waveform at the rising and falling edges of the trapezoid, as the voltage signal has overdriven the device past the peak and null of the modulator transfer function. The MZM $V_\pi$ is evaluated by projecting the overshoot peaks to the corresponding voltage levels. The peak-to-peak voltage used in the experiment was 10 V which was multiplied by the factor $b/a$ (inset of figure 3(b)) to obtain $V_\pi = 5.89$ V. The length ($L$) of the phase-shifter is 0.5 cm; therefore, the $V_\pi L$ of the modulator is 2.95 V-cm. This is a factor of 1.6 times lower (better) than our previously reported hybrid bonded LN modulator [33] due to the reduced electrode gap ($g$) from 12 to 8 µm. The measured $V_\pi L$ is in good agreement with the calculated $V_\pi L = (n_{eff} \lambda g)/(2n_e^3 r_{33} \Gamma_{mo})$, where $\lambda$, $n_e$, $r_{33}$, $n_{eff}$ and $\Gamma_{mo}$ are the optical wavelength, extra-ordinary refractive index of LN, EO coefficient of LN, the effective refractive index of the hybrid mode and the RF-to-optical mode overlap, respectively [34]. The EO coefficient ($r_{33}$) is 30.8 pm V$^{-1}$, while $n_{eff}$ and $\Gamma_{mo}$ values are extracted from eigenmode simulations (using Numerical MODE Solutions). Although further materials studies are to be performed, these results show that the EO properties
of the bonded thin-film LN were not affected by the long-term storage or any of the post fabrication processes that we performed.

The electro-optic response (EOR) of Group I and Group II devices were measured using continuous-wave lasers with nominal linewidth of 20 MHz and 200 kHz, respectively. A swept-frequency RF signal generator was used to generate sine waves and GSG probes were used for both launch and termination. The RF power delivered to the chip through the MZM transmission line was measured at the output using a high-frequency RF power sensor. The output of the sinusoidally driven modulator was measured using a high resolution optical spectrum analyzer (Finisar WaveAnalyzer 1500S) [57, 58]. This allowed us to record the carrier signal and the generated optical sidebands from modulation in 1 GHz steps from 1 to 50 GHz (figures 4(a) and (b)). The RF power generated by the swept-frequency source and delivered through the cables was measured separately using an RF power meter and a calibration substrate (CS-5, GGB Industries, Inc.). With this calibration data taken into account, the roll-off of the measured sidebands was calculated as a function of the sinusoidal modulation frequency (figures 4(c) and (d)), and defines the EOR. Based on the raw data shown in figure 4(a), figure 4(c) shows the normalized measured response (blue circles) with a 1.87 dB roll-off from 1 to 50 GHz of the Group I MZM. Similarly, based on the raw data shown in figure 4(b), figure 4(d) shows the normalized measured response (blue circles) with a 1.09 dB roll-off from 1 to 50 GHz of the Group II MZM. We also determined the RF characteristics of the two devices using the finite-element method and the hybrid bonded thin-film LN optical group index, resulting with a calculated 1–50 GHz roll-off of 1.77 dB for the Group I device and 1.42 dB for the Group II device [59]. Thus the calculated modulator frequency responses, the black lines shown in figure 4(c) and figure 4(d), are in good agreement with the measured values suggesting that the 3 dB bandwidth of the Si-LN MZMs exceeds 50 GHz in both cases and is quite similar. In the high speed measurements (GHz), there was negligible DC-drift because the EOMs were biased at quadrature by wavelength (with no DC voltage applied). However, a thorough study of low-frequency drift will require long term coupling, polarization, temperature, and electrical probing stability. Table 1 summarizes the performance of the Group I and Group II MZM devices and confirms that the long-term storage of pre-bonded devices (processed after three years) does not impact the optical and electrical performance of the hybrid bonded modulators.
5. Hybrid LN-Si photonic circuits

The ability to process the hybrid bonded thin-film LN devices after three years of storage on a shelf in a common lab environment and achieve comparable results to a freshly-fabricated chip allows for practical and useful flexibility in the process flow of integrated thin-film LN EOMs. This could be particularly useful for benefiting small-volume end users. For example, a batch of chips could be processed using Si wafer fabrication, diced, planarized and bonded at one facility at one time, and then divided into smaller lots for post-processing by the end users at different locations and at later times at their convenience. The separation of the SOI and LN layer and their respective functionalities also allows a wide range of device customization, as the Si layer can host a multitude of passive and active devices fabricated in a CMOS process at the same time as having a hybrid region dedicated to high bandwidth voltage-driven optical modulation.

There may be some changes required in the device design or fabrication process in order to facilitate this modular approach. For example, the standard Si-photonic optical devices are implemented on a SOI platform with 220 nm Si thickness, while this hybrid bonded platform uses a 150 nm thick Si layer, and therefore the rings, gaps and transitions must be redesigned. As an example, we demonstrate high-Q single microring resonators for narrow band single photon generation [60] and a cascaded three stage second-order coupled microring filters [61–64] in a SOI platform which is outside of the hybrid bonded MZM region (figure 5(a)) but part of the same chip. This structure is more functional but also more complex than our earlier report of hybrid circuits incorporating both LN and Si photonic segments [45]. Figure 5(b) shows the transmission spectrum through the symmetric-MZM (without modulation signal), single microring resonator and the three stage second-order coupled microring filters (Port 1 to Port 5 in figure 5(a)). The FSR, insertion loss, and the extinction ratio of the high-order filter are 5.0 nm, less than 1 dB, and greater than 40 dB, respectively. The measured filter FSR agrees precisely with the design target, and the filter extinction ratio is high, and is likely limited in figure 5(b) by the detection noise floor. The inset in figure 5(b) shows the transmission spectrum of the inline microring resonator with a loaded quality-factor (Q-factor) of $1.14 \times 10^5$, at 1556.96 nm. This is comparable to a standard high-Q Si microring resonator we have previously fabricated using conventional 230 nm Si thickness and used for photon-pair generation using spontaneous-four-wave-mixing [65].

To determine the performance of the hybrid bonded symmetric MZM, the input laser wavelength was positioned away from the single microring and higher-order microring filter resonances (Port 1 to Port 4 of figure 5(a)) and a DC voltage of 2.8 V was applied to set the quadrature bias point. The EOR was measured using the same method described in section 4, resulting with a 3-dB bandwidth greater than 50 GHz, as
Figure 5. (a) Schematic representation of a hybrid bonded thin-film MZM integrated with microring resonator based filters. (b) The measured transmission of a three stage second-order coupled microring filter cascaded with a ring resonator and symmetric hybrid bonded MZI fabricated using 150 nm thick Si waveguides. The inset shows the transmission spectrum of the micro-ring resonator with a loaded $Q$-factor of $1.14 \times 10^5$. (c) The measured EOR of the MZM from Port 1 to Port 4 such that the light was off-resonance from the filters, showing 3 dB bandwidth greater than 50 GHz. (d) The measured CAR values from the high-$Q$ Si microring at varying single photon rates. The inset shows a corresponding histogram of the signal and idler cross-correlation coincidence peak.

shown in figure 5(c). For testing purposes only, the microring resonator section was diced out to separately measure the coincidence-to-accidentals ratio (CAR) versus the single photon count rate. High CAR values were measured as shown in figure 5(d). The measurement to characterize the single photons from this portion of the chip was performed with superconducting nanowire single-photon detectors similar to a setup used in our prior report [65]. The photon rates and CAR were limited in this case by the coupling losses of the chip segment after dicing (17 dB). These promising early results indicate that our hybrid bonded platform, which brings LN and SOI devices together, can open new avenues for gated photon-pair generation, filtering, switching, wavelength-shifting of photons and quantum pulse gate operations [6].

The final-stage customization by the end user can also include thinning the LN film from the top surface [66], fabricating/depositing additional materials over the LN film, using doped variants of LN, and/or by modifying the CPW electrode design. For example, an EOM device for O-band wavelengths near 1310 nm requires a different LN film thickness for optimal performance compared to the C-band wavelengths near 1550 nm. To achieve this, one may thin the bonded LN film from the top using a procedure such as CMP, which has been shown to be compatible with bonded LN chips [49, 66–68] before fabricating the electrodes. None of these final-stage process steps require sub-micron alignment and can be done in most university-scale fabrication facilities. Such height trimming would be more difficult to achieve without potential damage if the LN was patterned into narrow ridges. Additionally, the RF dispersion can be engineered using slow-wave electrodes by introducing inductive or capacitive loading structures [69, 70]. The slow-wave electrodes provide extra design parameters for velocity matching (RF-to-optical), impedance matching and reduce the RF propagation loss [71–73]. These various types of customizations to the hybrid bonded MZM design can be implemented well after the LNOI chip has been bonded to the SOI chip.

6. Conclusion

In summary we observed that pre-bonded thin-film LN on Si MZM chips stored for an extended period (more than 3 years) can withstand Si handle removal, oxide etching, electrode fabrication and temperature cycles from the post-fabrication processes, which require no etching of the LN film. The test device has a measured $V_\pi L$ of 2.95 V cm and high-frequency roll-off exceeding 50 GHz and similar to the test device that
was freshly bonded without storage, when accounting for minor variations in the electrode design. Furthermore, we show the integration of hybrid bonded Si/LN MZMs with high quality narrow band quantum sources from Si photonic microrings (Q-factor of $1.14 \times 10^5$) and coupled microring filters (ER $> 40 \text{ dB}$) on a thinned Si platform. These results suggest the feasibility of a modular and scalable EOM fabrication approach that allows the separation of the processing steps. For instance, planarization and bonding of samples can be performed at one time, while smaller batches of chips can be customized by end users at a much later time as needed. This modular process would advance the foundry model for thin-film LN co-integration with conventional Si-photonics and benefit the development of both classical and quantum integrated photonics.

Data availability statement

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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Conflicts of interest

The authors declare no conflicts of interest.

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