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Simulation study of propagation losses due to sidewall roughness of GaAs waveguides for single-photon sources in quantum applications

(Student paper)

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Quantum optical technologies impose stringent requirements on device performance that may be overcome through photonic integration. In this work, we investigate light propagation losses incurred by sidewall roughness of GaAs waveguides used in single-photon sources, and the effect of this roughness on adiabatic coupling efficiency between GaAs and SiN.

Keywords: *Gallium arsenide, waveguides, propagation loss, sidewall roughness, coupling efficiency*

INTRODUCTION

Nowadays, quantum technologies present an important field of research and hold promise for many revolutionary applications. One of these technologies is quantum communication, which paves the way for a quantum internet and other applications. A key aspect of quantum communication technologies is their stringent requirements for device performance, such as very low optical loss and high indistinguishability of photons from single-photon sources. In addition to discrete system realizations for quantum communication, integrated solutions are also being explored [1].

Employing photonic integrated circuits, different components used in quantum communications can be integrated into a single chip through heterogeneous integration. In this regard, QuantERA project µTP4Q (A versatile quantum photonic IC platform through micro-transfer printing) aims to explore ways to integrate key components, such as InAs quantum-dot (QD) single-photon sources, $LiNbO_3$ modulators and switches, superconducting nanowire single-photon detectors, and low-loss passive circuitry based on a SiN platform [1], [2]. Heterogeneous integration of the components on a SiN interposer will be investigated by using the micro-transfer-printing (µTP) process [3]. This technique allows us to fabricate the components on their native platforms, select the best-performing devices, and subsequently integrate them into a single chip. It is essential that optical losses of the components and their interconnections are as low as possible. Therefore, highly efficient optical coupling between the interposer and transfer-printed components is required, as well as very low internal loss in components and in connection circuitry. Furthermore, for the actual implementation of such systems, it is important to consider fabrication-related effects, such as µTP-induced misalignment and light propagation loss caused by waveguide (WG) surface roughness.

In this work we study the optical losses in GaAs strip WGs for single-photon sources (including InAs QDs) associated with sidewall surface roughness. We quantify the light propagation losses with respect to randomly generated sidewall variations with different statistical parameters in simulations. The roughness can originate from different fabrication process steps, such as electron beam lithography and etching [4]. Secondly, we also show how such sidewall roughness of WGs affects the efficiency of adiabatic coupling between micro-transfer-printed GaAs WGs and SiN WGs of the interposer.

METHODS AND STRUCTURES

Simulations were performed with the finite-difference time-domain (FDTD) method using Ansys-Lumerical software. With respect to experimental observations, we applied the surface roughness to both sides of the GaAs WGs in the longitudinal direction. In our study we apply a generic randomly generated roughness to get a more general view and understanding of its effects in relation to its statistical parameters. No variations in the topology of the sidewalls were assumed in the vertical direction. Also, no roughness was applied to the top or bottom surface of the WGs either. This anisotropic sidewall roughness was characterised by its root-mean-square (RMS) value, σ_{rms}, and its correlation length, L_{corr}. The roughness was generated by employing the technique described in [5] and adapting existing scripts for random roughness generation available in Ansys-Lumerical software. The roughness functions on both sides of the WGs were uncorrelated. We chose the range of values for σ_{rms} and L_{corr}

based on preliminary measurements of actual samples using scanning electron microscopy [6]. Simulations were performed for a wavelength of 930 nm (central emission of InAs QDs) if not stated differently.

Fig. 1a shows the top view of a segment of a GaAs strip WG used in simulations (note the different scales of the vertical and horizontal axes), while Fig. 1b shows the top view and a cross-sectional view of a GaAs taper for adiabatic coupling to SiN WGs [3]. In the first case, the isolated WG is surrounded by air entirely and has a base cross-section of 300 nm in width and 170 nm in height. In both types of simulations, the fundamental TE mode transmission (T_{TE1}) is the primary parameter of interest. The refractive index of the bonding layer (BCB) was set to 1.54, while for other materials the corresponding refractive indices were taken from the material library of the simulation tool. According to the available values for the extinction coefficient, no material absorption was considered at the given wavelength.

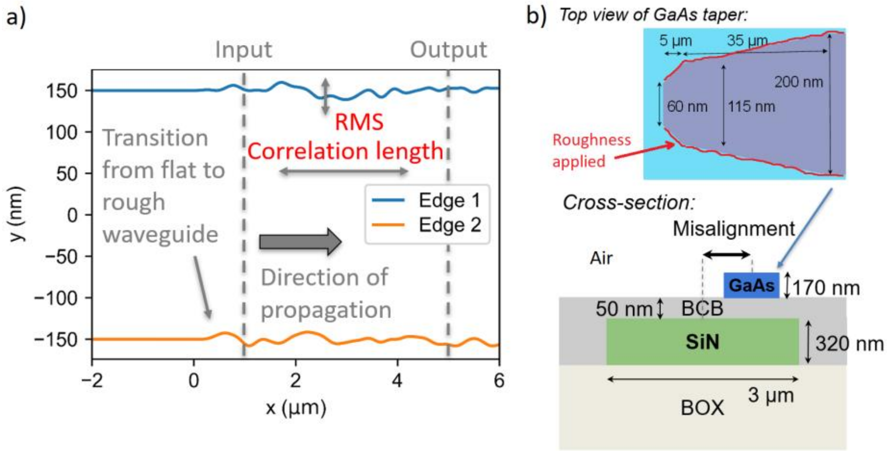

Fig. 1. a) Example of sidewall variations and setup of simulations for an isolated GaAs WG. b) Structure for the GaAs-SiN adiabatic coupler as used in simulations.

RESULTS

The results of simulations of GaAs WGs with sidewall roughness as a function of σ_{rms} and L_{corr} are presented in Figs. 2a and 2b, respectively. A 4 µm long WG section was included in the propagation loss calculations based on these simulations. The symbols in the plots represent simulations with different pseudo-random number generator (PRNG) seeds, while the curves represent the average of 10 simulations with different seeds at a given value of the x-axis parameter. It can be observed that an increase in σ_{rms} or a decrease in L_{corr} leads to a substantial increase in propagation losses. It should be noted that a large spread of the loss values is obtained by varying the PRNG seed. Therefore, in addition to σ_{rms} and L_{corr}, the spatial frequency spectra of the randomly generated roughness were also considered (see insets). In the two cases shown in Fig. 2b, it can be observed that the power spectra of the sidewall variations of the WG with lower loss (right inset) are shifted towards higher spatial frequencies compared to the WG with higher loss (left inset).

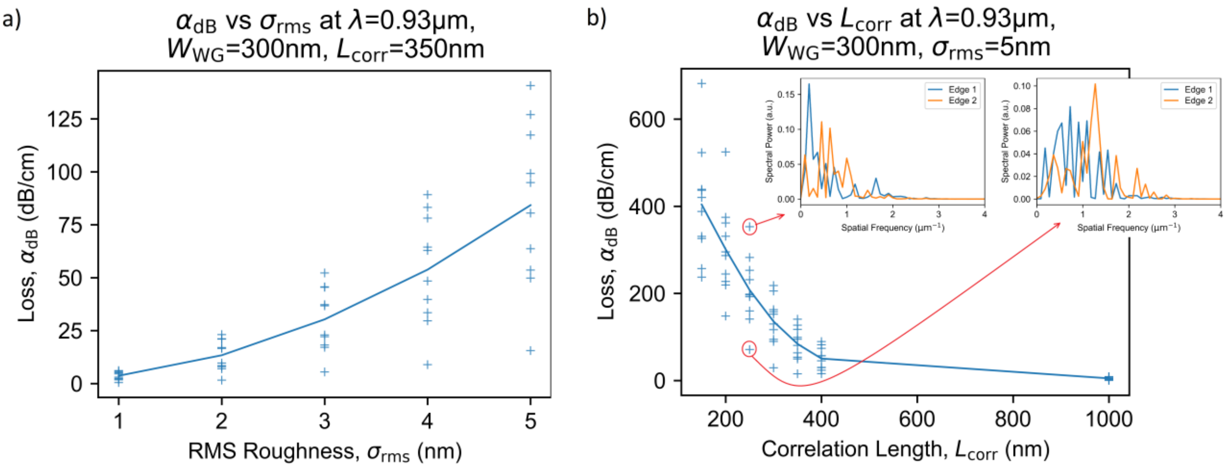

Fig. 2. a) Simulated propagation loss of rough GaAs WGs with respect to RMS roughness for a 350 nm correlation length. b) Simulated propagation loss of rough GaAs WGs with respect to correlation length for a 5 nm RMS roughness. The insets show the power spectra of the sidewall variations for two GaAs WGs used in simulations.

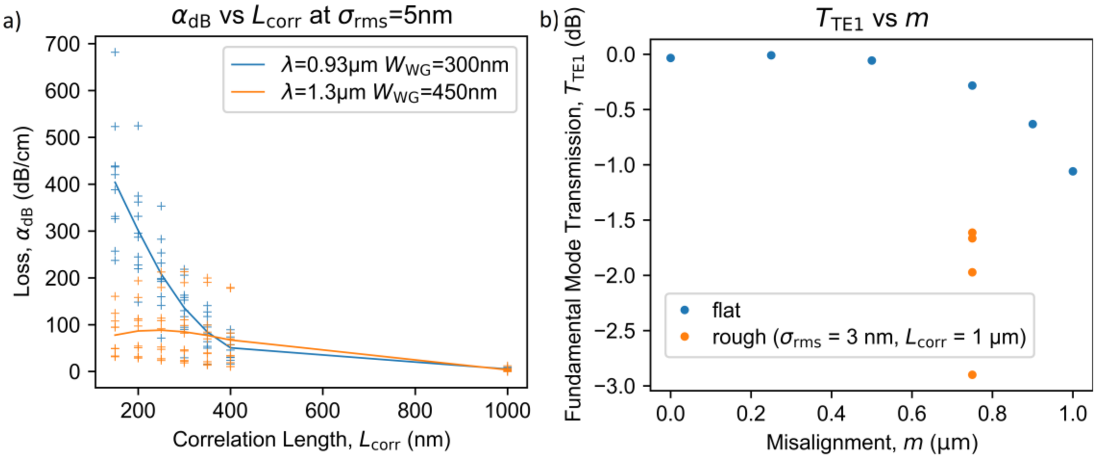

Fig. 3. a) Simulated propagation loss of rough GaAs WGs with respect to correlation length for a 5 nm RMS roughness and two WG types differing in width and target wavelength of operation. b) Simulated fundamental TE mode transmission of the GaAs-SiN adiabatic coupler with respect to misalignment for an ideally flat GaAs WG and additional points for the case of a rough GaAs WG at a misalignment of 0.75 µm and four different PRNG seeds.

From the results presented in Fig. 2, it is clear that sidewall roughness can be the cause of losses in GaAs WGs from below 10 dB/cm to greater than 400 dB/cm. In the parameter range where the simulations were performed, low L_{corr} (below 300 nm) leads to high losses in the hundreds of decibels per centimeter. In our conference presentation we will link these values with experimental observations on fabricated GaAs WGs, reaching values of 50-70 dB/cm.

To indicate the role of wavelength with respect to the losses, in Fig. 3a we also show simulation results for a wavelength of 1300 nm (also using a wider WG – 450 nm, still assuring single-mode operation for this wavelength). In this case, we can observe that the increase in losses associated with a low L_{corr} is much smaller – the average losses remain below 100 dB/cm, whereas they exceed 400 dB/cm for the initial waveguide at a 930 nm wavelength.

In Fig. 3b we show preliminary results of the effect of GaAs WG sidewall roughness on the efficiency of the GaAs-SiN adiabatic coupler shown in Fig. 1b with respect to the misalignment of the two WGs caused by the µTP process (see misalignment definition in Fig. 1b). It is clear that the sidewall imperfections have a significant impact on the performance of such couplers, as the fundamental TE mode transmission of a coupler with flat GaAs WG sidewalls decreases from -0.3 dB to around -2.0 dB on average (with respect to the PRNG seed) for a selected misalignment of 0.75 µm when rough sidewalls are used. Further results will be shown in the conference presentation.

CONCLUSIONS

We performed a simulation study on the propagation losses of GaAs WGs due to sidewall roughness as a function of σ_{rms} and L_{corr}. It was shown that for σ_{rms} of a few nm and for L_{corr} below 300 nm very high losses (above 100 dB/cm) occur. Using a wider WG and longer wavelength can result in substantially lower loss in case of short correlation lengths. Furthermore, we showed preliminary results on the effect of GaAs WG sidewall roughness on the performance of a GaAs-SiN adiabatic coupler.

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