Analysis of optical losses of GaAs waveguides for single-photon sources considering realistic waveguide roughness

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ABSTRACT

Photonic integrated circuits are a promising technology for quantum applications, which are known to impose stringent requirements on the performance characteristics of utilized components. Besides achieving high efficiency of active photonic components, low optical losses of waveguiding and coupling structures are of the same importance. In this contribution we focus on the analysis of optical losses related to waveguiding of single photons generated by InAs quantum dots in GaAs strip waveguides. We perform a simulation study of the effects of GaAs waveguide nanoscale surface roughness on the waveguide propagation losses. This study is also supported by experimental data on line edge roughness and surface roughness of fabricated GaAs waveguides determined from SEM and AFM analyses. The roughness applied in simulation is based on the statistical properties of this data. The results of our analysis strengthen our understanding of scattering losses and their individual contributing factors. We also conclude that for the investigated GaAs waveguides the contribution of scattering on the waveguide top surface roughness to the propagation losses is very small compared to the contribution of sidewall scattering.

Keywords: quantum photonic integrated circuits, gallium arsenide, waveguide, sidewall roughness, surface roughness, propagation loss, sidewall scattering.

1. INTRODUCTION

Photonic integrated circuits (PICs) hold promise for many revolutionary applications, including quantum technologies. Applications in the quantum domain impose stringent requirements on the performance characteristics of utilized components. Besides achieving high efficiency of active photonic components (single-photon sources, single-photon detectors, modulators), low optical losses of waveguiding and coupling structures are of the same importance.

In this contribution we research and analyze optical losses related to waveguiding of single photons generated by InAs quantum dots (QDs) in GaAs strip waveguides around the wavelength of 930 nm in the quasi-TE guided mode [1][2]. Minimisation of the current state of propagation losses in GaAs waveguiding structures (~7 dB/mm) can significantly contribute to the overall performance of single-photon sources in quantum PICs [3]. Here, we focus on the contribution of the scattering of light on realistic nanoscale surface roughness of GaAs strip waveguides to the total propagation losses. We model the waveguides using the finite-difference time-domain (FDTD) method, paying special attention to properly include and simulate nanoscale roughness profiles on micrometer-long GaAs waveguides. In our analysis we include sidewall and top surface roughness based on measurements of fabricated waveguides. Sidewall roughness can in our case be attributed mainly to the e-beam fabrication process, while the top surface roughness is attributed mainly to etching and cleaning processes during fabrication. The statistical characteristics of the roughness were determined from line edge roughness extracted from SEM images and surface roughness extracted from AFM images of fabricated GaAs waveguides. To better understand and quantify the effects of this nanoroughness, in our simulation study we performed additional variation of parameters such as roughness RMS value and correlation length. We also compare our simulation results with measured ~7 dB/mm propagation loss of fabricated GaAs waveguides published in [3].

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2. METHODS

The statistical characteristics of roughness are commonly modelled by fitting an exponential or a gaussian function to the autocorrelation function (ACF) of the roughness [4][5]. We chose the exponential function as it seems more common and appears to fit our data better. The exponential autocorrelation function (ACF), R_{rr}, is given by

$$R_{rr} = \sigma^2 \mathrm{e}^{-\frac{|r|}{L_c}}, \qquad (1)$$

where r is the correlation lag parameter, σ is the roughness RMS value, and L_c is the correlation length.

Since waveguide sidewall roughness is mainly attributed to the e-beam fabrication process, only roughness in the longitudinal direction of the waveguide is considered. Sidewall roughness was imaged with a Jeol JSM-7800F by placing the sample flat in the vacuum chamber (no tilt) and capturing images of 5 different waveguide segments from the top. Line edge roughness was extracted from the captured images with the ProSEM software and analyzed in Python.

Top surface roughness was imaged using a Bruker Dimension Icon AFM tool with the sample placed flat in the working area. The image was analyzed with the Gwyddion software.

Simulations of GaAs waveguides with applied surface roughness were performed with the 3D FDTD method implemented in the Ansys-Lumerical FDTD software. Due to the nanometer-scale features present in the waveguide model, a fine simulation mesh is required, and the total simulation domain length is limited by computation time. Therefore, the waveguide length is limited to the micrometer range. Since the scattering losses of nanoscale surface roughness along a micrometer-long waveguide are small, extensive convergence analyses were performed to ensure that simulation results are accurate.

In simulation, no material absorption was considered. Top surface and sidewall roughness were simulated separately to decouple their individual contribution to the total propagation losses. To generate roughness profiles for individual waveguide simulations, a random spectrum was created with a pseudo-random number generator (PRNG) with a uniform distribution. In the case of sidewall roughness, the spectrum was one-dimensional, and in the case of top surface roughness it had two dimensions. The zero-frequency term of the spectrum was set to zero. The spectrum was then multiplied with a filter obtained by applying the Wiener-Khinchin theorem—relating the ACF to the power spectral density—to the exponential ACF given by Eq. 1. To obtain the final roughness profile, the filtered spectrum was scaled to achieve the target RMS and transformed by the inverse discrete Fourier transform. Different profiles sharing the same statistical parameters were obtained by changing the PRNG seed.

3. RESULTS

The nominal GaAs strip waveguide cross section used in fabricated devices is 300 nm in width and 170 nm in height. Technically, this results in a multi-mode waveguide, as the first higher-order TE mode is present. However, it is very poorly confined to the waveguide core. The measured sidewall roughness RMS value is around 2 nm and correlation length around 50 nm. Simulations were performed for wavelengths between 880 nm and 980 nm. The roughness applied to the waveguide surfaces was computer-generated, considering the nominal statistical parameters. The analysis was additionally extended to RMS values and correlation lengths from 0.5 nm to 10 nm and 10 nm to 300 nm, respectively.

Fig. 1 presents the propagation losses of simulated waveguides with sidewall roughness and no top surface roughness. The results of simulations considering the nominal parameters are shown in Fig. 1a. A decreasing trend in losses with increasing wavelength is observed. The error bars show the standard deviation of the results of multiple simulations with different roughness profiles, but the same statistical parameters. There is a large difference (~4 dB/mm) between the losses at wavelengths 880 nm and 980 nm. The analysis showed that the large increase in losses for shorter wavelengths within the simulation bandwidth is mostly due to coupling to the first higher-order mode, which we consider as loss. To clarify, as wavelength decreases towards the lower end of our simulation wavelength range, more power is coupled from the fundamental TE mode to the first higher-order TE mode.

In Fig. 1b, the effect of roughness RMS value variation on propagation losses is shown. Attenuation of 7 dB/mm is reached around the 3 nm RMS mark, which is already in agreement with [3], where the estimated RMS is 3–4 nm. However, this agreement should be considered qualitatively, as there is some uncertainty associated with measurement and statistical modelling of roughness.

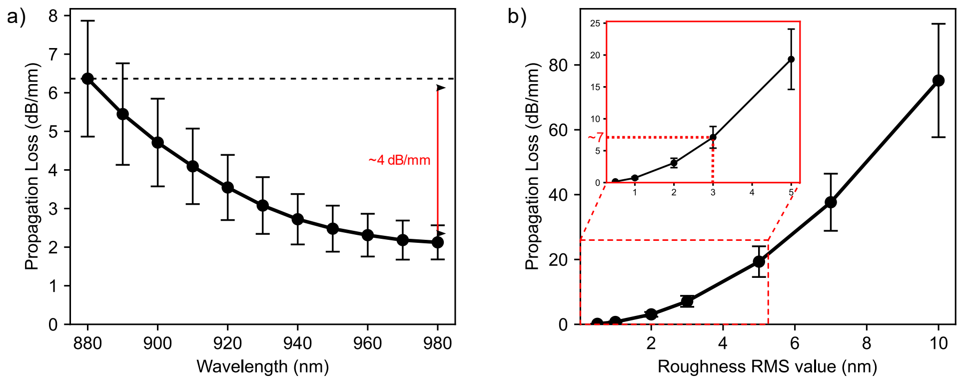

Figure 1. 3D FDTD simulation results for GaAs waveguide propagation loss due to sidewall scattering, considering a 300 nm × 170 nm cross section and 50 nm correlation length. (a) Wavelength dependence of losses for a 2 nm roughness RMS value. (b) RMS dependence of losses for a 930 nm wavelength.

Compared to sidewall roughness, the measured top surface roughness is substantially smaller for our waveguides. Measured RMS is around 0.5 nm and correlation length is below 10 nm. However, it is important to quantify the effects of this roughness on losses. Fig. 2 shows the simulated propagation losses due to top surface scattering with respect to roughness RMS value at a 930 nm wavelength for two correlation lengths (10 nm and 50 nm). The sidewall roughness was set to zero in this case to clearly identify the effect of top surface roughness alone. Looking at the 50 nm correlation length and 3 nm RMS value, a 3 dB/mm loss is observed, which is 4 dB/mm lower than in the case of sidewall scattering. This lower loss could be due to the 2D nature of the applied roughness or a different field distribution at the top surface as opposed to the sides for the fundamental TE mode. However, further analyses are required in this domain. At the measured values of RMS and correlation length, simulated losses are below 0.1 dB/mm. Since this is nearly two orders of magnitude lower than the contribution from sidewall roughness, the effect of top surface roughness can be disregarded in this case.

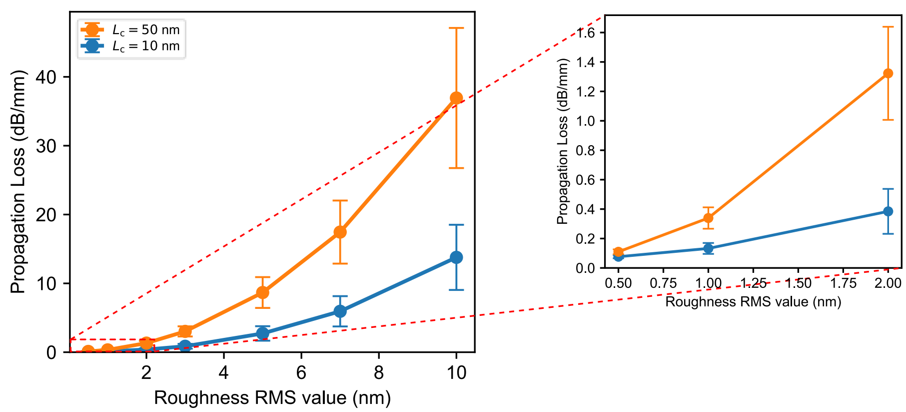

Figure 2. 3D FDTD simulation results for roughness RMS value dependence of GaAs waveguide propagation loss due to top surface scattering considering a 300 nm × 170 nm cross section and a 930 nm wavelength.

4. SUMMARY

We have briefly discussed our methodology and simulation results of our analysis of GaAs waveguide surface roughness in the context of propagation loss in QD single-photon sources for QPICs. We showed selected results of our simulation study and linked them to experimentally observed propagation losses published in [3]. Although the results are in agreement with [3], they are primarily of qualitative value due to some uncertainty associated with measurement and statistical modelling of roughness. We have further concluded that the contribution of the top waveguide surface roughness to the total propagation losses is exceedingly small compared with the contribution of sidewall scattering and can be disregarded in this case. The results of our analysis strengthen our understanding of scattering losses and their individual contributing factors. In our conference presentation we will show additional results, also considering different waveguide widths.

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