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ABSTRACT

We report on the analysis of electroabsorption in thin GaAs/Al_{0.3}Ga_{0.7}As nanophotonic waveguides with an embedded p–i–n junction. By measuring the transmission through waveguides of different lengths, we derive the propagation loss as a function of electric field, wavelength, and temperature. The results are in good agreement with the Franz–Keldysh model of electroabsorption extending over 200 meV below the GaAs bandgap, i.e., in the wavelength range of 910–970 nm. We find a pronounced residual absorption in forward bias, which we attribute to Fermi-level pinning at the waveguide surface, producing over 20 dB/mm loss at room temperature. These results are essential for understanding the origin of loss in nanophotonic devices operating in the emission range of self-assembled InAs semiconductor quantum dots toward the realization of scalable quantum photonic integrated circuits.

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An ambitious goal in photonic quantum technologies is to scale up photonic integrated circuits for generating, routing, and detecting single photons efficiently. One of the fundamental challenges is to keep the overall device and circuit loss as low as possible, as the fundamental no-cloning theorem of quantum mechanics forbids amplification of the single-photon signal. Gallium arsenide (GaAs) membranes with embedded self-assembled quantum dots (QDs) constitute a mature platform for integrating deterministic single-photon emitters with planar photonic integrated circuits14 with excellent single-photon source performance.15 Furthermore, the integration of doped layers in the epitaxial heterostructure enables building thin p–i–n diode junctions to control the state and charge occupation of the QD to reduce electrical noise2 and to tune the emitter wavelength via the quantum-confined Stark effect.3 At the same time, however, the doped layers introduce additional loss due to free-carrier absorption and the Franz–Keldysh effect (FKE).10 The latter originates from the strong built-in electric fields in such thin junctions, which distort the electron and hole wave functions in GaAs and enable optical absorption at energies below the bandgap.

In this work, we report on a detailed analysis of various attenuation mechanisms in doped GaAs waveguides. We analyze the impact of electroabsorption and surface states on the waveguide loss. From the observed results, we conclude that a significant contribution to electroabsorption originates from strong band bending at the surface of the waveguide, which is caused by mid-gap surface states. Previous works suggested that loss in doped waveguides can arise from unpassivated surfaces,11,12 but no quantitative analysis has been reported. By comparing measurements with and without doped layers and at different temperatures, we can identify the origin of loss and devise a strategy for designing and fabricating the next generation of quantum photonic integrated devices with quantum emitters.

The devices used in this work are single-mode rectangular waveguides fabricated on a 180-nm-thick GaAs/Al_{0.3}Ga_{0.7}As membrane with a width of 300 nm. The layout of the structure and the profile of the fundamental transverse electric (TE) mode, E_y(x, z), are shown in Figs. 1(a) and 1(b), respectively. The heterostructure contains a p–i–n diode with a 100 nm-thick undoped region and a layer of self-assembled InAs QDs located in the middle. The Al_{0.3}Ga_{0.7}As layer above the QDs serves as a barrier to reduce the tunneling rate of holes out of the QDs, thereby extending the Stark tuning range of the emitter.13 Further details on the heterostructure used in this work are given in Ref. 4. Figure 1(c) shows the diode band diagram at T = 6.5 K, calculated using a one-dimensional Poisson equation solver,14 when no external voltage is applied to the diode. The solid lines show the
conduction and valence band in the case of perfect Ohmic contacts to the $p$- and $n$-type layers. In a more realistic scenario, the waveguide surfaces have been exposed to air and have oxidized, producing a large amount of defects whose energy level is located within the GaAs bandgap. These mid-gap states are populated causing a net increase in surface charge density. The presence of surface defects is known to "pin" the Fermi level inside the gap, causing band bending in the proximity of the surface. To model the effect of the Fermi-level pinning, we apply a Schottky-type boundary condition with a barrier height of $1 \text{ eV}$ on both sides of the diode. The Schottky barrier height is estimated assuming a density of surface states of $\sim 10^{13} \text{ cm}^{-2}$, which pins the Fermi level $\sim 0.5 \text{ eV}$ above the valence band maximum, as reported in previous experiments. The bending of conduction and valence bands is shown in Fig. 1(c) as dashed lines. The corresponding electric field (with and without band bending) is plotted in Fig. 1(c) (right axis). Fields exceeding $1 \text{ MV/cm}$ appear at the top surface due to Fermi-level pinning. Such large fields are expected to contribute significantly to the absorption due to the FKE, even several hundreds of meV inside the gap, where excitonic states of QDs are located. The surface field is independent of the applied bias, allowing us to separate the contribution to electro-absorption due to band bending from the bulk absorption.

To model the Franz–Keldysh absorption $\alpha_{FK}(\lambda, F)$ as a function of wavelength $\lambda$ and electric field $F$, we use the model by Callaway, with the phenomenological scaling factors reported in Ref. 19. These models and experiments cover the wavelengths (910–970 nm) and the electric field ranges of our experiment, but have been only experimentally validated at room temperature and in bulk GaAs. We assume that a change in temperature only affects the bandgap of GaAs, shifting it from $E_g = 1.44 \text{ eV}$ at room temperature to $E_g = 1.52 \text{ eV}$ at $T = 6.5 \text{ K}$, resulting in a lower absorption at cryogenic conditions. The calculated bulk absorption for the two temperatures used in this work, together with the inhomogeneous distribution of QD emission, is shown in Fig. 1(d). The dotted lines show the typical zero-field absorption of direct-gap undoped semiconductors, i.e., when no absorption is expected at energies below the bandgap.

From the electric field profile $F(z)$ calculated in Fig. 1(c) and the FKE model $\alpha_{FK}(\lambda, F(z))$, a profile of the electroabsorption as a function of the position $z$ in the waveguide can be derived, which is plotted in Fig. 1(e). Here, we only plot the absorption due to the built-in electric field ($V_{bi} \approx 1.52 \text{ V}$) and surface fields due to Fermi-level pinning, while we neglect the electroabsorption in the $Al_{0.3}Ga_{0.7}As$ region, as the bandgap is further blue-shifted to $1.77 \text{ eV}$. We further separate the contribution to the total absorption in two spatially distinct regions: (1) the undoped region inside the $p$–$n$–$n$ junction, where the absorption depends on the externally applied bias [solid line in Fig. 1(e)], and (2) the surface regions, where the absorption is only due to Fermi-level pinning and does not depend significantly on the external field (dashed lines). We model the total loss in the waveguide as

$$\alpha(\lambda, F) = \alpha_0(\lambda) + \Gamma_b \alpha_{FK}(\lambda, F),$$

where $\alpha_0(\lambda)$ is the residual absorption (i.e., without the voltage-dependent FKE) and $\Gamma_b$ is the mode confinement factor for the undoped GaAs region, given by the overlap integral

$$\Gamma_b = \frac{e}{2n} \int_0^b \frac{\langle S_y(x, z) \rangle \langle \tilde{E}(x, z) \rangle^2 dx dz}{\langle S_y(x, z) \rangle dx dz}. \tag{2}$$

Here, $S_y(x, z)$ and $\langle \tilde{E}(x, z) \rangle$ are the simulated two-dimensional profiles of the optical mode electric field (cf. Fig. 1(b)) and of the average Poynting vector component in the propagation direction of the
waveguide, respectively, while $\varepsilon(x, z)$ is the spatial distribution of the permittivity. Subscript $b$ denotes the undoped (bulk) GaAs layer in the waveguide. The electric field in the undoped region is calculated using $E = (V_{\text{bi}} - V)/d$, where $d$ is the total length of the undoped and depletion layer and $V_{\text{bi}}$ is the built-in voltage of the diode junction.

To measure the loss per unit length in nanophotonic waveguides, a series of concentric waveguides have been fabricated on the sample following the procedure outlined in a previous work. The gratings are written using electron-beam lithography and etched via reactive ion etching in the same run, to ensure high reproducibility of their transmission spectrum within a 10% error. Figure 2(a) shows a top-view scanning electron microscope (SEM) image of the fabricated sample. The p-contact electrode is highlighted in yellow, and it is used to apply a voltage to the $p-i-n$ junction in the GaAs membranes. A pair of gratings are used to couple light in and out of the waveguides. The gratings are placed at a fixed distance from each other, to avoid re-aligning the position and angle of excitation and collection beams, and cross-polarized to avoid collecting any scattered light from the input ports. This method allows factoring out the loss due to the gratings and the three 90-degree bends. Several tethers are used to keep the waveguide suspended in air, as shown in the inset of Fig. 2(a).

Varying the number of tethers per unit length does not affect the transmission in our experiments, and therefore, we assume all tethers to be lossless. The sample is mounted in a closed-cycle cryostat, and transmission measurements are performed using a supercontinuum laser source. Figure 2(b) shows the transmission spectra of the shortest waveguide $L = 95 \mu m$, at cryogenic and room temperature, without any bias applied to the diode. A visible quenching of the transmission is observed at room temperature, due to the built-in electroabsorption. Due to the thermo-optic effect, the grating transmission peak red-shifts by roughly 20 nm at room temperature. The small absorption. Due to the thermo-optic effect, the grating transmission peak red-shifts by roughly 20 nm at room temperature. The small absorption.

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To identify the various contributions to loss in doped waveguides, the applied bias is varied from $V = +0.6$ V (forward bias) to $V = -4$ V (reverse bias) in steps of 0.4 V and the measurement and fitting procedure described in Fig. 2 is repeated at all voltages. Figure 3(a) shows the dependence of the waveguide loss $\alpha$ as a function of the applied bias for three different wavelengths at $T = 6.5$ K and for the peak wavelength of $\lambda = 950$ nm at room temperature. Error bars are given on the logarithmic scale by propagation of uncertainties after fitting. A non-linear least squares fitting procedure is used to fit the data with the model of Eq. (1), where the fitting parameters are the confinement factor of the undoped region $\Gamma_0$ and the residual loss. The residual loss $\alpha_R$ is plotted in Fig. 3(b) as a function of wavelength and temperature. This is the loss that remains after compensating the built-in voltage in the waveguide. The pronounced wavelength dependence of such residual loss suggests that an additional FKE is present, most likely due to the surface fields caused by Fermi-level pinning. We note that the loss per unit length extracted at wavelengths away from the grating peak would generally be more sensitive to variations between different samples. Nonetheless, all data analysis was carried out in a parameter range where such sample variations were minor compared to the extracted propagation loss.

To confirm this, the residual loss is fitted as a function of wavelength using the FKE model,

$$\alpha_R(\lambda) = \alpha_0 + \Gamma_s \alpha_{FC}(\lambda, F_b),$$

where we use a fixed field of $F_b = 0.65$ MV/cm obtained from the simulated average surface field [cf. dashed line of Fig. 1(c)]. From the fit, the confinement factor of the surface region $\Gamma_s$ and the background loss $\alpha_0$ are extracted. The solid lines show the best fit to the data. The results of the two fits of Fig. 3 are summarized in Table I and comparable to theoretical values obtained from finite-element calculations.

Both low-temperature and room-temperature fits result in a constant background loss of $\alpha_0 = (11 \pm 2)$ dB/mm. Such a loss can be attributed to the sum of two main contributions, namely, free-carrier absorption ($\alpha_{FC}$) and intrinsic loss ($\alpha_{INT}$). Free-carrier absorption is estimated using the data for p-doped and n-doped layers given in Ref. 24 and scaled by the confinement factors of Eq. (2), resulting in $\alpha_{FC} \sim 4$ dB/mm. Intrinsic loss of waveguides is measured on a separate experiment that uses undoped wafers but identical waveguide geometry. The results have been previously published in Ref. 23 and resulted in $\alpha_{INT} \sim 7$ dB/mm. The main source of intrinsic loss is suspected to be caused by scattering due to sidewall roughness arising in the GaAs etching process. The root-mean square (RMS) roughness in our waveguides is estimated to be in the range of $\sim3$–$4$ nm from SEM analysis. According to waveguide scattering theory such as the Payne–Lacey model, roughness causes unwanted coupling between the fundamental guided mode and radiation modes, which is stronger for high-index contrast waveguides. A full three-dimensional finite element simulation of transmission over rough waveguides provides a loss in the range of $5$–$8$ dB/mm, consistent with our experimental findings. Another potential loss mechanism is given by the aforementioned mid-gap states, which, even in the absence of doped layers, can cause absorption below the bandgap energy. However, further experiments are required to reduce the scattering loss and observe such loss mechanisms.

In conclusion, we have reported the analysis of electroabsorption in gated GaAs nanophotonic waveguides as a function of voltage.
wavelength, and temperature. While the fundamental building blocks and devices for quantum applications can be realized over small (<100 μm) dimensions, where the losses are negligible, scaling up photonic integrated circuits in doped GaAs requires a deep understanding of the origin of such losses. To this end, it is crucial to devise a method to remove the sources of absorption while still operating at λ ~ 930 nm, i.e., the central wavelength of high-quality QDs. The p-doped layer is the largest source of free-carrier absorption, and it is only required in the emitter region. By selectively etching away the p-layer from the surface, the free-carrier absorption can be reduced to $\alpha_{FC} \sim 0.5 \text{ dB/mm}$ (i.e., the $n$-layer contribution) and the FKE due to built-in fields can be suppressed. Surface fields, however, require strategies for unpinning the Fermi level. Several works have shown that oxide removal followed by surface passivation greatly enhances the quality factor of microdisks, photonic crystal cavities, and vertical microcavities.\textsuperscript{11-14,22,23} By removing mid-gap states, it is expected that the surface Fermi level unpins, thereby removing any source of electro-absorption due to band bending. Finally, improving the fabrication process using intermediate hard masks\textsuperscript{22} or resist reflow\textsuperscript{29} is also expected to reduce the waveguide RMS roughness to < 1 nm, which can potentially reduce the intrinsic waveguide loss down to $\alpha_{NT} < 1 \text{ dB/mm}$. Achieving such a target would enable integrating several hundreds of devices, such as single-photon sources, filters, and switches, while taking advantage of the small size of such devices in the GaAs platform. For example, recently reported nano-mechanical switches and filters\textsuperscript{28,29} have footprints of ~25 μm, which would allow implementing large (>40-mode) unitary gates with an optical depth of ~1 mm, required for photonic quantum information processing.

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### DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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