

## Propagation Loss in *GaN*-based Ridge Waveguides

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**Abstract:** *GaN* ridge waveguides were fabricated by selective area growth in an Organometallic Vapor Phase Epitaxial system. The growth enhancement on a  $3.5\mu\text{m}$  wide exposed channel versus the masked area width was measured. The propagation losses of a series of *GaN* multimode waveguides, with different widths, were measured by the out-scattering technique at  $\lambda=488\text{nm}$ . The internal optical loss of the *GaN* ridge waveguide was found to be  $\alpha_{\text{int}} \sim 4.45\text{cm}^{-1}$ . Sidewall scattering loss ( $\alpha_{\text{scat}}$ ) and the additional optical loss due to metal electrodes were also measured. The fabricated waveguides may be a basic component for integrated optic circuits.

Recent progress in *GaN*-based light emitters<sup>1,2</sup> and detectors<sup>3,4</sup> motivates the development of optical waveguides<sup>5</sup> with the future prospect of integrated optical systems (*IO*), implemented monolithically in the *Ga(Al, In)N* material system.

Selective area growth (*SAG*) is based on the fact that there is no material growth on regions of a wafer covered by a dielectric material such as silicon dioxide or silicon nitride. Thus, by dielectric coating and patterning the underlying epitaxial substrate, the growth proceeds selectively only on the exposed (unmasked) regions. It has been shown that the dislocation density of *GaN* films produced by *SAG* is reduced and the material quality is improved.<sup>6</sup> Furthermore, the side-facets of *GaN* structures, fabricated by this technique, are found to be smooth and flat. The advantages of *SAG* for guiding light in *GaN* structures were also reported by ref. 7.

Here we report on the fabrication of low loss ridge waveguides for visible wavelength formed by a *GaN* core and  $Al_xGa_{1-x}N$  claddings, grown by *SAG*, in an Organometally Vapor Phase Deposition System (*OMVPE*). Guided light transmission ( $\lambda=488nm$ ) over a distance of  $\sim 1cm$  is demonstrated, thus showing the feasibility to use these waveguides as the basic component of a *GaN*-based *IO* circuit.

A *GaN* low-temperature buffer layer is grown on sapphire followed by the growth of a  $1\mu m$  thick  $Al_xGa_{1-x}N$  ( $x \approx 0.15-0.2$ ) layer and a  $500\text{\AA}$  *GaN* layer (base layer). The growth is performed by *OMVPE*, using the previously described technique.<sup>8</sup> After the base layer growth,  $2000\text{\AA}$  of  $SiO_2$  was deposited by plasma enhanced chemical vapor deposition (*PECVD*) and patterned with long lines parallel to the  $\langle 11\bar{2}0 \rangle$  direction by using conventional photolithography and buffered *HF* etching. The wafer was then loaded back into the *OMVPE* chamber for the *SAG* of a *GaN* core layer and a thin  $Al_xGa_{1-x}N$  (upper cladding) layer.

The growth rate of the *GaN* layer in the thin lines (in the re-growth step) is dramatically enhanced as the ratio of the exposed areas to masked areas decreases.<sup>9</sup> In order to find the relation between the width of the masked zones and the growth enhancement of the *GaN* film, a mask of *SiO<sub>2</sub>* was patterned into  $3.5\mu\text{m}$  wide open lines surrounded by masked areas. The width of the *SiO<sub>2</sub>* areas,  $d$ , was varied along each line in the range of  $3\text{-}250\mu\text{m}$ . The surface of the wafer after re-growth is shown on Figure 1. The cross-sectional shape of the *GaN* channel is also dependent on the *SiO<sub>2</sub>* width. Scanning Electron Microscope (*SEM*) pictures of this shape in two different regions are shown on the insets of Figure 1. The measured growth enhancement as a function of  $d$  is presented on Figure 2. We find that a growth enhancement of  $\sim 7$  is possible for  $d \geq 150\mu\text{m}$ . However, due to increased roughening of the sidewalls of the ridge for large values of  $d$ , the conservative value of  $d \approx 50\mu\text{m}$  was chosen for waveguide fabrication.

*GaN*-based ridge waveguides were fabricated according to the above described procedure, with various widths ( $W$ ):  $3.5, 4.5, 6.5, 8.5, 11.5, 15.5$  and  $20.5\mu\text{m}$ . Cleavage was used to separate bars containing waveguides  $\sim 1\text{cm}$  long.

In order to measure the optical losses of the slab *GaN* waveguides, we used a  $\lambda=488\text{nm}$  Argon laser (*TE* polarization). The light was inserted into a fiber and then coupled to the *GaN* waveguide by a *X-Y-Z* micropositioner. The light guiding was confirmed by an optical system consisting of an objective lens and a CCD camera, which was focused on the output facet of the waveguide. The propagation losses of the waveguides were measured by the out-scattering technique. In this technique a fiber probe is utilized to measure the light scattered from the surface of the waveguide (normal to the wafer plane). An implicit assumption in this measurement is that the out-scattered light intensity is proportional to the guided light intensity. The fiber

probe is a  $62.5\mu\text{m}$  core multimode fiber ended with a lens. The out-scattered light intensity,  $I_{scat}(z)$ , was sampled every  $50\mu\text{m}$  along the waveguide axis ( $z$  direction). A chopper and a lock-in-amplifier were utilized for synchronous detection of the intensity of the light, collected by the fiber probe. Figure 3(a) is a schematic description of the measurement set-up. Figure 3(b) shows  $I_{scat}$  vs. distance along the propagation direction,  $z$ , for an  $8.5\mu\text{m}$  wide waveguide. The experimental values of  $I_{scat}(z)$  are well approximated by an exponential decay:  $I_{scat}(z) \sim I_{scat}(0)\exp(-\sigma z)$ .

The simple exponential decay is not expected “a-priori” since each one of the guided modes may be attenuated at a different rate. The measured attenuation in terms of a single loss parameter,  $\sigma$ , can be justified by invoking the formalism of propagation loss in multimode waveguides of refs. 10-11.

Waveguide imperfections cause coupling among forward traveling modes. The change in the average power of mode  $n$ ,  $P_n$ , is defined<sup>10</sup> by:

$$dP_n / dz = -2\alpha_n P_n + \sum_{v=1}^N h_{nv} (P_v - P_n) \quad (1)$$

where  $h_{nv}$  represents the power coupling coefficient ( $h_{nv} = h_{vn}$ )<sup>10</sup> and  $2\alpha_n$  is the power loss coefficient. We define  $2\alpha_n = \alpha_{int} + \alpha_{scat, n}$ , where  $\alpha_{int}$  represents the total material losses and  $\alpha_{scat, n}$  is the external scattering of mode  $n$  (caused by interface roughness). By substitution of

$$P_v(z) = A_v \exp(-\sigma z) \quad (2)$$

into Eq. (1), we get a system of first order differential equations. The eigenvalue  $\sigma$  represents the modal losses.<sup>12</sup>

As long as steady state among the modes is not yet reached, the decrease of the power depends on the power distribution between the modes. However, once the steady state is reached, the average power carried by each mode decreases at the same rate, so that the total power distribution decreases without change of its shape.<sup>10</sup> As a result of that, the propagating light intensity in a multimode waveguide at the steady state decays exponentially.<sup>10</sup>

The losses caused by external scattering can be estimated by measuring the roughness of the channel walls,  $\sigma_w$ <sup>13</sup>:

$$\alpha_{\text{scat},n} = K^2 \left( \frac{1}{2} f(\theta_n) \frac{1}{W + 1/r_n + 1/p_n} \right) \quad (3)$$

where  $K = (4\pi/\lambda)\sigma_w$ ,  $\lambda$  is the wavelength in the film,  $f(\theta_n) = (\cos^3 \theta_n / \sin \theta_n)$ ,  $\theta_n = \arcsin(\lambda\beta_n/2\pi n_{\text{eff}})$ <sup>13</sup>,  $\beta_n$  is the propagation coefficient of the  $n$ th mode,  $p_n$  and  $r_n$  are the transverse decay constants of the  $n$ th mode in the cladding layers.  $\beta_n$ ,  $p_n$ ,  $r_n$  and  $n_{\text{eff}}$  can be calculated by the effective index method.<sup>14</sup>

Since  $W \gg \lambda$ , the relation  $1/r_n, 1/p_n \ll W$  is satisfied for all the guided modes. The power distribution among the modes in waveguides of our type is almost identical,<sup>11</sup> therefore we may write the average value  $\overline{f(\theta_n)}$  as a constant in Eq. (3):

$$\sigma \sum_{n=1}^N A_n^{(1)} = \left( \alpha_{\text{int}} + K^2 \overline{f(\theta_n)} \frac{1}{2W} \right) \sum_{n=1}^N A_n^{(1)} \quad (4)$$

Eq. (4) suggests that the waveguide losses are of the form  $\sigma \sim \alpha_{\text{int}} + B/W$  ( $B$  constant). For  $W \rightarrow \infty$  the average decay constant equals to the internal material losses,  $\sigma = \alpha_{\text{int}}$ . The measurement of  $\sigma$  vs.  $W^{-1}$  are presented at Figure 4, with best fit to the linear equation:  $\sigma = 4.4524 \text{ cm}^{-1} + 10.552(\mu\text{m}/\text{cm}) / W$ , thus,  $\alpha_{\text{int}} = 4.4524 \text{ cm}^{-1}$  and by

using Eq. (3)  $\sigma_w$  is estimated to be  $\sim 130nm$ , in reasonable agreement with topographic measurements of the samples.

In order to estimate the possibility of implementing active electro-optic devices using *GaN* multimode waveguides, a  $1000\text{\AA}$  of  $SiO_2$  layer was deposited on the wafer after re-growth. Electrodes were formed on the waveguides by sputtering *Ni/Au* layers  $200\text{\AA}/2000\text{\AA}$  thick using a conventional lift-off technique. The waveguides were covered with  $2mm$  long metal stripes. For using the out-scattering technique, a series of open windows ( $15\mu m$  long) were left in the metal contacts every  $50\mu m$ . The scattered light was measured as described before. The measurement results of the light scattered from a  $4.5\mu m$  wide waveguide are presented on

Figure 5. The loss coefficient in the metal covered areas is  $\sigma_{metal} \approx 12cm^{-1}$ .

In summary, in this work we presented *GaN*-based multimode waveguides, fabricated by the selective area growth technique. The relation between the width of the masked zones and the height of the *GaN* channel was measured for  $3.5\mu m$  open lines. The *GaN* material optical losses at  $488nm$  were calculated by measuring the propagation loss of various widths *GaN* channel multimode waveguides.

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## Figure Captions

Figure 1 – Scanning Electron Micrograph (SEM) pictures of the surface of a wafer after re-growth. The bright zones are  $GaN$  and the dark zones are  $SiO_2$ . In the middle there is a  $3.5\mu m$  wide  $GaN$  channel (SAG), surrounded by different size ( $d$ )  $SiO_2$  masks. In the insets are SEM pictures of the cross-sectional shape of the  $GaN$  channel at different regions.

Figure 2 - The normalized  $GaN$  channel height as a function of  $SiO_2$  mask width,  $d$ .

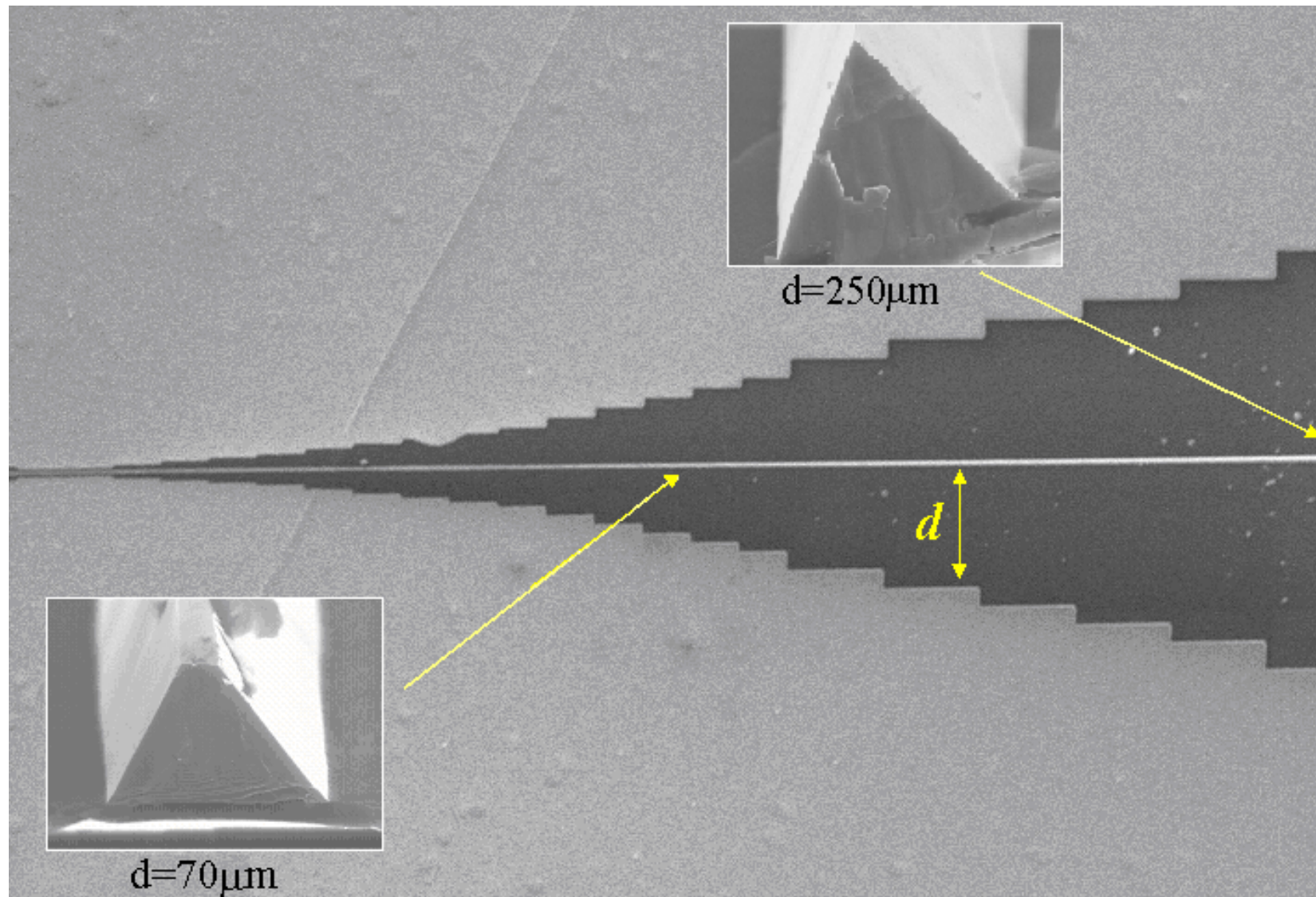
Figure 3 – (a) – Schematic description of the measurement set-up.  $F_1, F_2$ : optical fibers,  $I_{in}, I_{out}, I_{scat}$ : input, output and scattered light intensity, respectively.

(b) – A typical measurement of  $I_{scat}$  vs. distance along the propagation direction of an  $8.5\mu m$  wide waveguide.

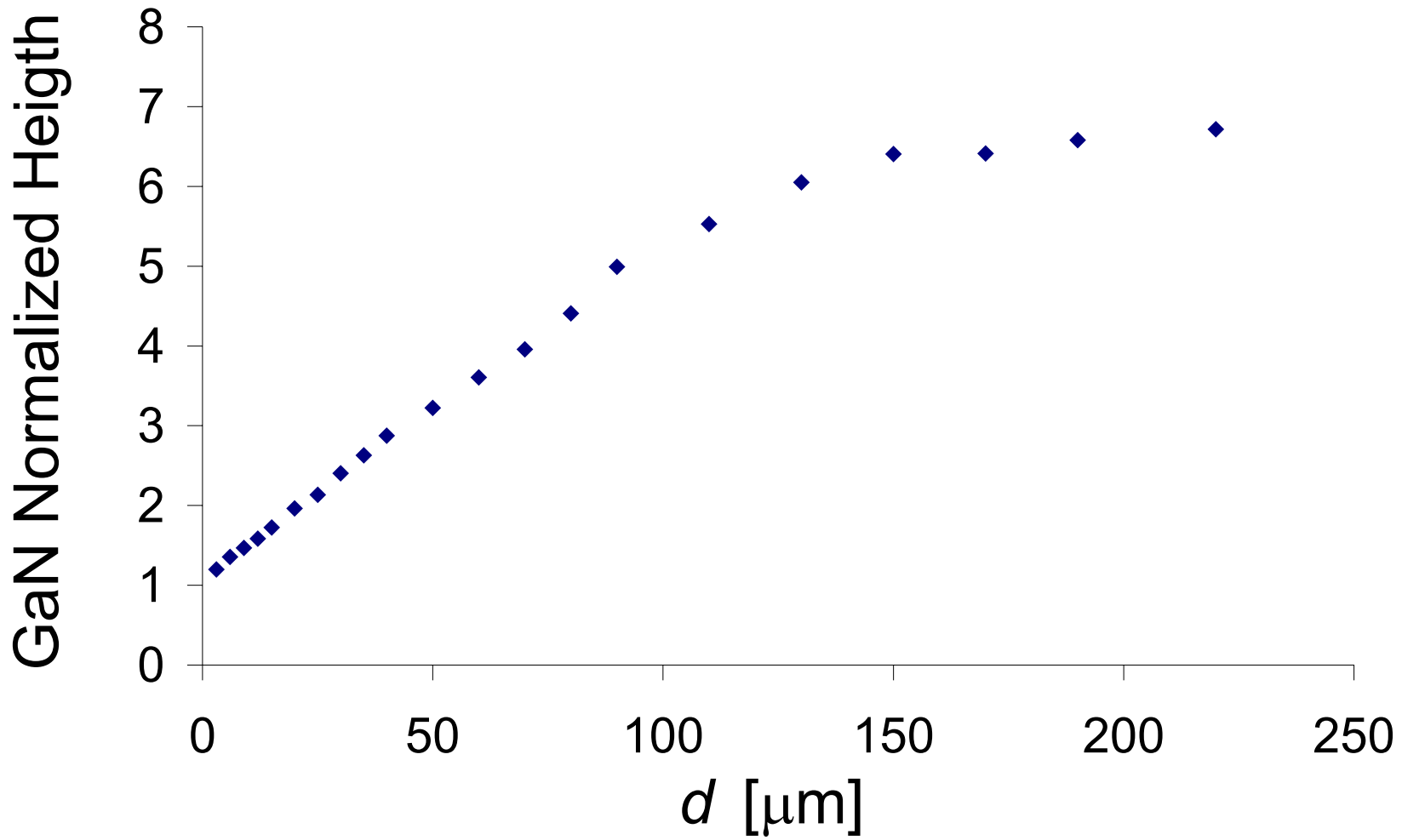
Figure 4 - Propagation loss coefficient,  $\sigma$  vs.  $l/W$ .

Figure 5 – A typical measurement of the light scattered from a  $4.5\mu m$  wide waveguide with a  $2mm$  long section covered with metallization.





**Figure 1**



**Figure 2**

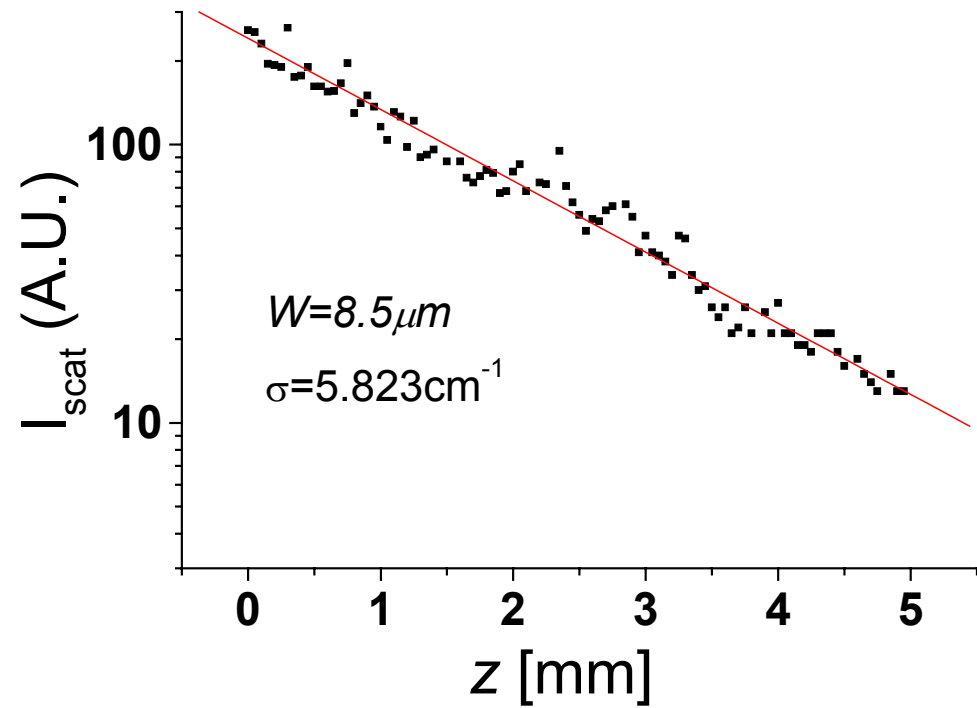
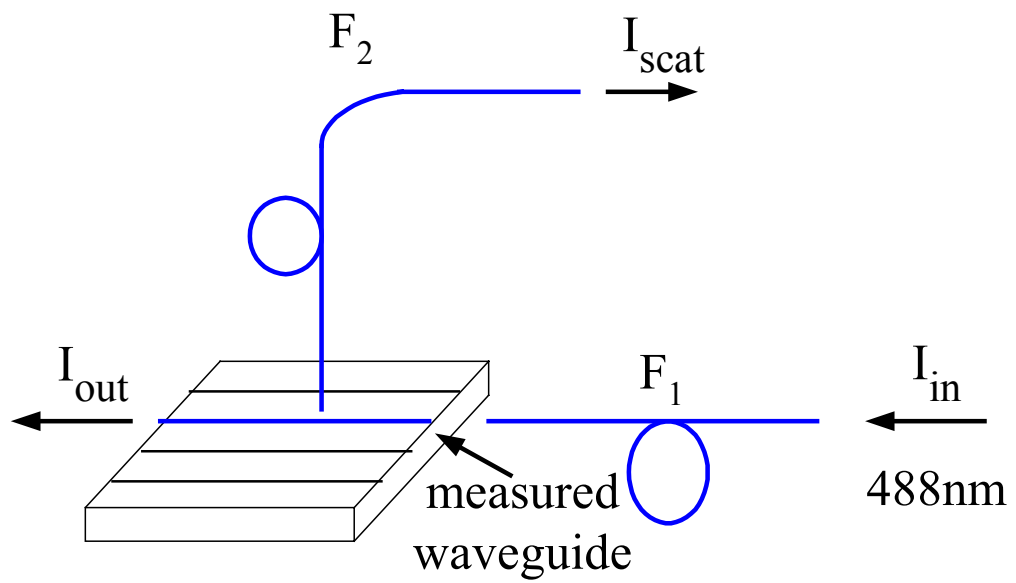
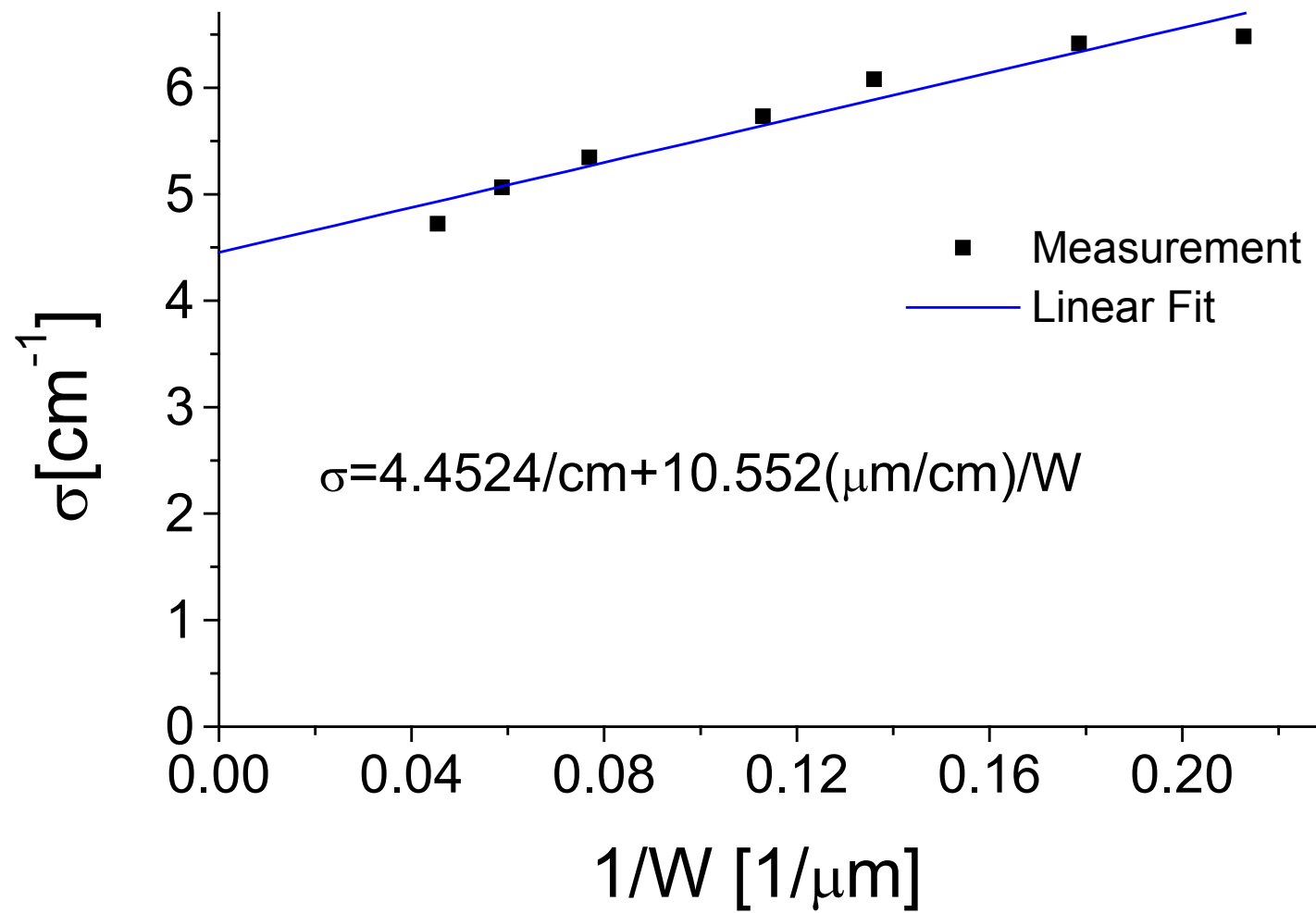


Figure 3



**Figure 4**

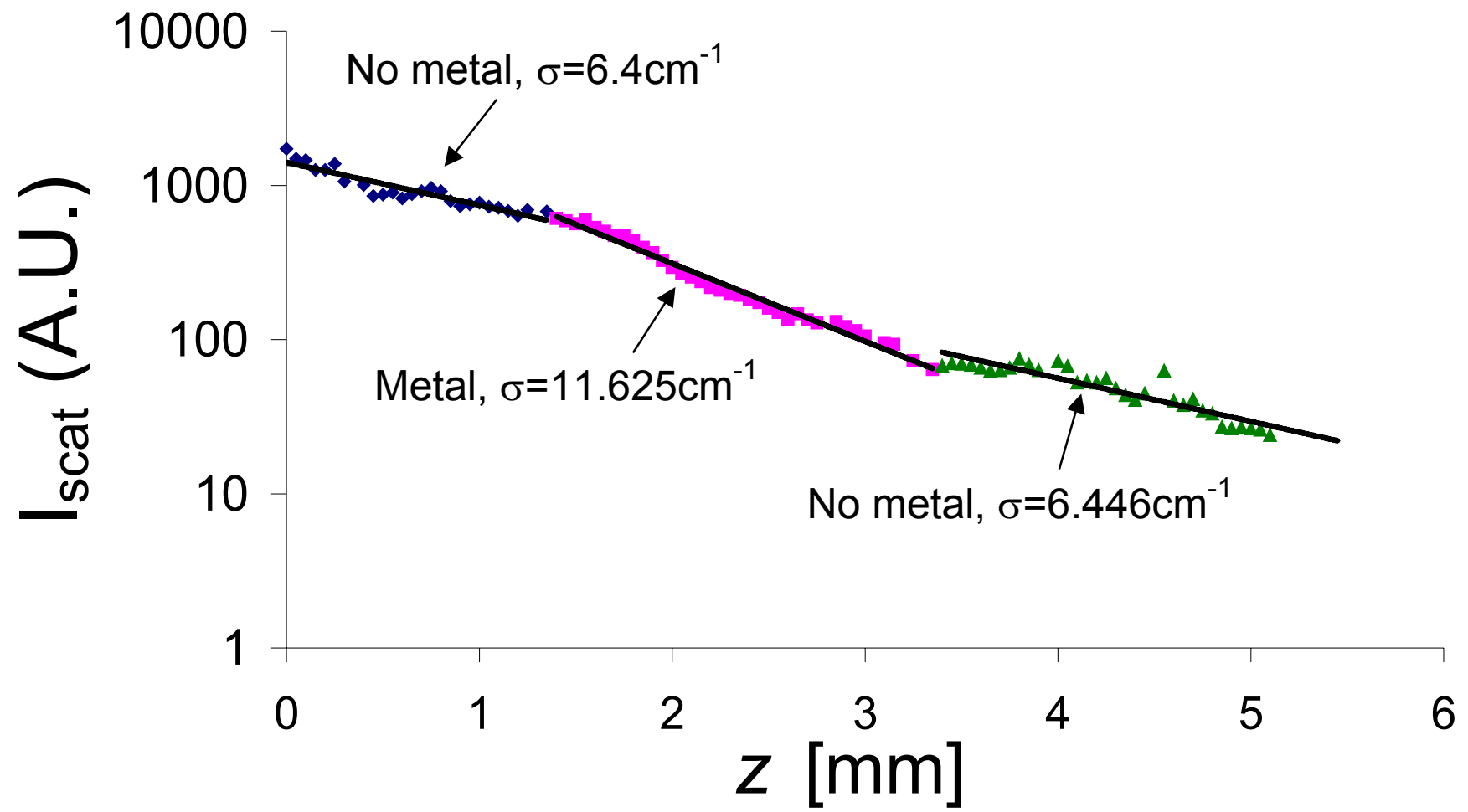


Figure 5