(a) With $\overline{i_s} = i_s = 411\ \mu\text{A}$, the shot noise at $T = 300$ K is

$$\overline{i^2_{\text{n,sh}}} = 2eB\bar{i} = 2eB\left(\overline{i_s} + \overline{i_d}\right)$$
$$= 2 \times 1.6 \times 10^{-19} \times 150 \times 10^6 \times \left(411 \times 10^{-6} + 10 \times 10^{-9}\right)\text{A}^2$$
$$= 1.97 \times 10^{-14}\ \text{A}^2.$$

The shot noise at $T = 273$ K is

$$\overline{i^2_{\text{n,sh}}} = 2eB\bar{i} = 2eB\left(\overline{i_s} + \overline{i_d}\right)$$
$$= 2 \times 1.6 \times 10^{-19} \times 150 \times 10^6 \times \left(411 \times 10^{-6} + 4 \times 10^{-9}\right)\text{A}^2$$
$$= 1.97 \times 10^{-14}\ \text{A}^2.$$

The shot noise is the same at $T = 300$ K and $T = 273$ K because $i_d \ll i_s$.

(b) With $R \approx R_L = 50\ \Omega$, the thermal noise at $T = 300$ K is

$$\overline{i^2_{\text{n,th}}} = \frac{4k_BTB}{R} = \frac{4 \times 25.9 \times 10^{-3} \times 1.6 \times 10^{-19} \times 150 \times 10^6}{50}\text{A}^2 = 4.97 \times 10^{-14}\ \text{A}^2.$$

The thermal noise at $T = 273$ K is

$$\overline{i^2_{\text{n,th}}} = \frac{4k_BTB}{R} = \frac{4 \times 23.5 \times 10^{-3} \times 1.6 \times 10^{-19} \times 150 \times 10^6}{50}\text{A}^2 = 4.51 \times 10^{-14}\ \text{A}^2.$$

The thermal noise at $T = 300$ K is proportionally higher than that at $T = 273$ K.

(c) At $T = 300$ K, the SNR is

$$\text{SNR} = \frac{\overline{i^2_s}}{\overline{i^2_n}} = \frac{\overline{i^2_s}}{\overline{i^2_{\text{n,sh}}} + \overline{i^2_{\text{n,th}}}} = \frac{\left(411 \times 10^{-6}\right)^2}{1.97 \times 10^{-14} + 4.97 \times 10^{-14}} = 2.43 \times 10^6 = 63.9\ \text{dB}.$$

At $T = 273$ K, the SNR is

$$\text{SNR} = \frac{\overline{i^2_s}}{\overline{i^2_n}} = \frac{\overline{i^2_s}}{\overline{i^2_{\text{n,sh}}} + \overline{i^2_{\text{n,th}}}} = \frac{\left(411 \times 10^{-6}\right)^2}{1.97 \times 10^{-14} + 4.51 \times 10^{-14}} = 2.61 \times 10^6 = 64.2\ \text{dB}.$$

(d) When the photocurrent is proportionally reduced to $i_s = 41.1\ \mu\text{A}$ for an optical signal of $P_s = 100\ \mu\text{W}$, the shot noise is reduced but the thermal noise remains unchanged. From (c), we find that the SNR is almost entirely determined by the thermal noise because the shot noise is negligibly small compared to the thermal noise at $i_s = 411\ \mu\text{A}$. At $i_s = 41.1\ \mu\text{A}$, the shot noise is even smaller, with $\overline{i^2_{\text{n,sh}}} \approx 1.97 \times 10^{-15}\ \text{A}^2$. At $T = 300$ K, the SNR is

$$\text{SNR} = \frac{\overline{i^2_s}}{\overline{i^2_n}} \approx \frac{\overline{i^2_s}}{\overline{i^2_{\text{n,th}}}} = \frac{\left(41.1 \times 10^{-6}\right)^2}{1.97 \times 10^{-15} + 4.97 \times 10^{-14}} = 3.27 \times 10^4 = 45.1\ \text{dB}.$$

At $T = 273$ K, the SNR is

$$\text{SNR} = \frac{\overline{i^2_s}}{\overline{i^2_n}} \approx \frac{\overline{i^2_s}}{\overline{i^2_{\text{n,th}}}} = \frac{\left(41.1 \times 10^{-6}\right)^2}{1.97 \times 10^{-15} + 4.51 \times 10^{-14}} = 3.59 \times 10^4 = 45.6\ \text{dB}.$$

Because the photodetector is thermal-noise limited, the SNR is reduced by two orders of magnitude, i.e., by 20 dB, when the signal current is reduced by one order.