

## CCD pixels: More is not necessarily better in a TEM Camera?

### 1. “Do more pixels in a CCD camera necessarily mean higher image resolution?”

Most people believe this to be the case when purchasing a CCD camera for TEM work. This may seem so obvious that no explanation is needed. However, this is not a trivial question. Consider the following related question:

*“How do you know that all the pixels are contributing to improved resolution?”  
Keep in mind that image processing can add many additional pixels to the digital image, with no improvement in image resolution.*

Certainly, no one would purchase a TEM based solely on the highest magnification achievable. The reason is that the magnification of a TEM is not related to its achievable resolution. If structural detail is not resolved by the objective lens which is the first imaging lens in a TEM, subsequent magnification by the projector lens system will not improve the final image resolution. In this case, increased magnification by the projector lens system can be considered as “empty” magnification since it cannot improve the image resolution.

Similarly, all elements in a CCD TEM camera can influence the final image resolution. The figures below help to illustrate this.

Let’s consider two CCD camera systems. They both have the identical scintillator and optical system (optical fiber is used in the illustration, but the concept also applies to optical lens). The only difference is that CCD#1 uses a CCD sensor with smaller pixel size as compared to CCD#2.

For simplicity, optical fiber size is not drawn to proportion with respect to CCD pixel size.

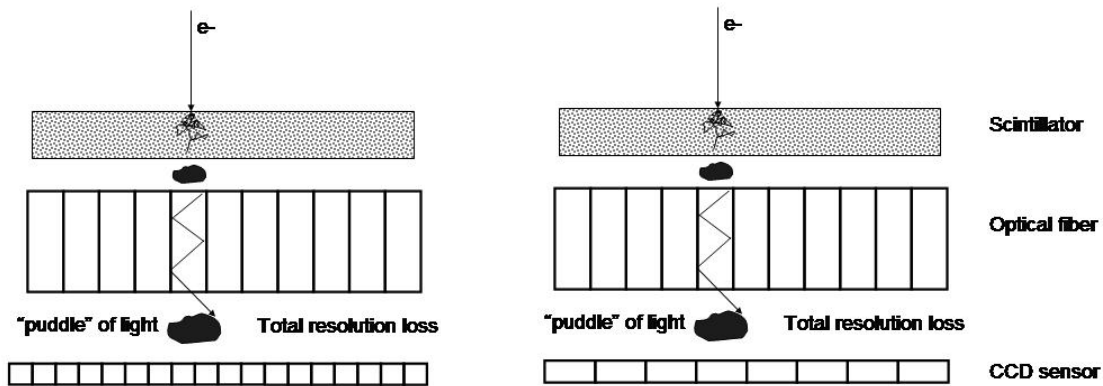


Fig.1a - CCD#1 with small pixel size

Fig.1b - CCD#2 with large pixel size



### Inherent Resolution Loss

A CCD sensor does not directly detect the fast primary electrons that form an image in the TEM. These fast electrons must first be converted into a light signal using a thin layer of material known as a “scintillator”. The fast electrons undergo a scattering process in the scintillator as they generate light. In this process, electrons deviate significantly from their original paths after the random scattering. As a result, the resolution of the light image is worse than the original electron image of the sample. The control and minimization of this image resolution loss during the fast electron-to-light conversion is a critical technology in the design of a high-resolution CCD camera.

Additionally, either an optical-fiber or an optical-lens coupling method is used to transmit the light signal to the CCD sensor. In the coupling process, the light image could possibly further lose resolution due to light scattering in the optical fibers or imperfect optical lens system.

Consequently, the *total resolution loss*, due to the scintillator and the optical fiber or lens components is directly related to the quality of CCD camera design; hence it is a critical performance parameter. In another words, a fast electron impinging on the scintillator generates a light "puddle" due to the total resolution loss, rather than a single ‘point’. It is this "puddle" that is imaged by the CCD sensor (Figure 1).

### Importance of Pixel Size

In order to understand the resolution of a CCD camera, one must take into account the total resolution loss as described above, and the CCD pixel size. In the optimal design of a CCD camera, the pixel size of the chosen CCD sensor should match (or get as close as possible) the size of the "puddle" because the "puddle" comes from a single point produced by a single fast electron in the original image. Ideally this “puddle” should correspond to a single pixel in the detected image. If the CCD pixel size is smaller than the "puddle" as in most CCD camera designs, a single point in the original image would be spread out over several pixels in the detected image. This is called "smearing" since the detected image has lost the "sharpness" of the original image. In this case, the CCD camera will have poor resolution regardless of the number of pixels in the CCD sensor!

Therefore, it is only when the "puddle" and the CCD pixel have the same (or similar) size that more pixels mean more resolution. Ignoring the resolution loss issue represented by the "puddle" and only emphasizing the number of pixels in a CCD camera is a meaningless exercise because the most critical issue in image resolution has not been considered. In the analogy with TEM resolution, it is like ignoring the quality of the objective lens, and merely focusing on the highest magnification of a TEM. No matter how many pixels in the CCD camera, if the "puddle" size is larger than the CCD pixel size, the CCD camera will contain "empty pixels" because these pixels do not improve the image resolution.



**2. "How can one tell if all pixels in a CCD camera contribute to improved resolution?"**

The most straightforward way to test this is to use the "line resolution test" as used in all optical instrument testing. The basic idea is simply to test the minimum distance (line pairs) that a CCD camera can resolve. Below is a procedure.

- Choose a test sample that contains periodic features. A crystalline sample such as graphitized carbon or gold particles is ideal if the TEM is capable of resolving the periodicity. If not, other samples that contain larger periodicity should be used.
- Set the CCD camera to 1x binning mode, i.e. the recorded image will have as many pixels as the CCD camera.
- Set the TEM magnification high enough so that the periodic lines are visible (resolved) in the recorded CCD image.
- Lower the magnification and record the image that corresponds to the lowest magnification where the periodic lines are still visible.
- Measure the distance of the line pairs in CCD pixels. If the total resolution loss (the "puddle") is about the same size as the CCD pixel, one would find that the distance of the line pairs in the recorded image is about the size of 2 pixels (fig.2b). Otherwise, one would find the distance of the line pair is much larger than the size of 2 pixels (fig.2a).

*The "2-pixel per line pair" is the well known Nyquist digital sampling theorem, which describes the limit of using discrete points to represent continuous signal.*

- Only when a pair of lines is resolved with approximately 2 pixels, can one conclude that all pixels in the CCD camera contribute to the improved resolution! (*Otherwise, the CCD camera is considered to contain meaningless (empty) pixels.*)

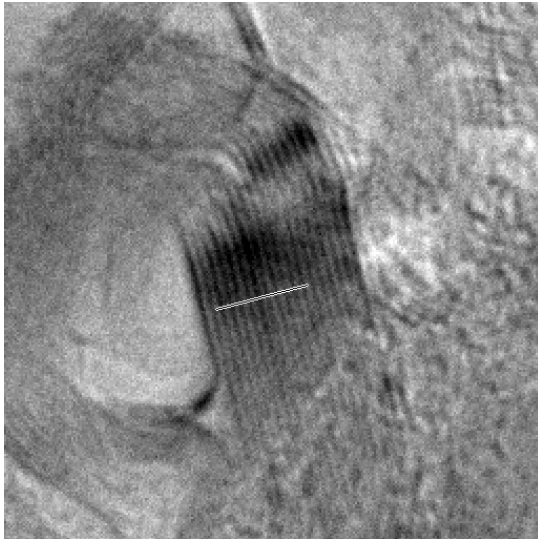


Fig. 2a (CCD#1)  
 Lowest magnification TEM image of  
 graphitized carbon lattice fringes.  
 10 line pairs = 45 pixels.  
 Each line pair = 4.5 pixels.

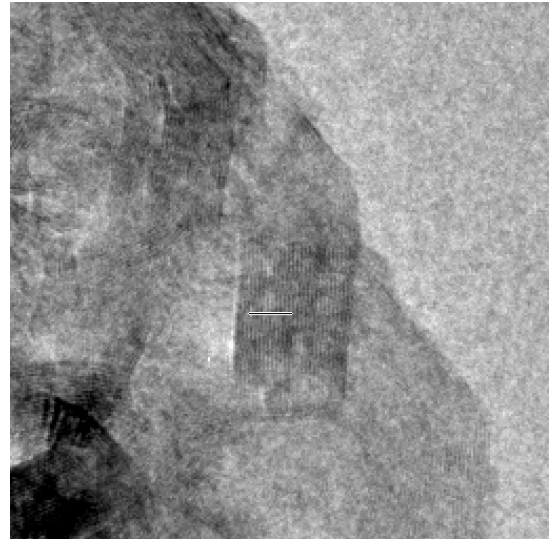


Fig. 2b (CCD#2)  
 Lowest magnification TEM image of  
 graphitized carbon lattice fringes.  
 10 line pairs = 21 pixels.  
 Each line pair = 2.1 pixels.

### 3. Conclusion

The number of pixels in a CCD camera does not define its resolution. The true and meaningful resolution can only be obtained by matching the CCD pixel size with the size of the electron generated “puddle” or the total resolution loss. It is only under such condition that more pixels result in higher image resolution.

For CCD cameras that generate the “puddle” with size larger than a single pixel, in order to achieve the true single pixel resolution, one need combine the CCD pixels to form a “super pixel” so that it has the similar size as the “puddle”. For example one can combine 2 pixels in x and 2 pixels in y direction, termed 2 x 2 binning. Then the real effective pixels in the CCD camera are 4 times less than original number of pixels! For example, if the original number of pixels is 2k x 2k or 4 Megapixels, then the real effective pixel in this camera is only 1k x 1k or 1 Megapixels!

*(The intention of this note is to make the reader aware that buying unused pixels is really a waste of money as well as not guaranteeing improved resolution.)*