of reduced light, and corresponding information, that passes through the slit. The tradeoff between resolution and throughput is very hard to overcome by a physical spectrometer design alone.

SUMMARY

[005] Embodiments of the present disclosure seek to mitigate the above-described tradeoff with physical design parameters associated with conventional spectrometers.

[006] Embodiments of the present disclosure seek to enable use of a low resolution spectrometer to collect spectral data and be able to resolve finer details within the spectral data or images without sacrificing throughput or spectral range.

[007] According to a first aspect of the present invention, there is provided an apparatus that includes a data acquisition instrument that observes a state of a semiconductor fabrication process and generates a data set accordingly. The data acquisition instrument is a spectrometer that generates electromagnetic spectral data as the data set. The apparatus also includes memory circuitry that stores the data set indicative of the state of the semiconductor fabrication process or of semiconductor structure fabricated thereby. Features in the data set are discernable to an extent limited by a data resolution. The memory circuitry also stores a machine-learning model comprising parameters having respective values assigned thereto as constrained by a model training process. The machine-learning model being a pyramidal residual convolutional neural network. The memory circuitry also stores a training data set containing features that are discernable to an extent limited by a training resolution that is greater than the data resolution. The apparatus further includes processor circuitry that is communicatively coupled to the memory circuitry and generates an output data set from the data set in accordance with the machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set. the spectrometer includes an entrance slit and a grating, the training data set includes low resolution training data and high resolution training data that are acquired from the spectrometer, and the grating is located closer to the slit when the low resolution training data are acquired than when the high resolution training data are acquired.

[007a] According to a second aspect of the present invention, there is provided an apparatus that includes a data acquisition instrument that observes a state of a semiconductor fabrication process and generates a data set accordingly. The data acquisition instrument includes a rough spectrometer and a detailed spectrometer that generate electromagnetic

spectral data as the data set. The apparatus further includes memory circuitry that stores the data set indicative of the state of the semiconductor fabrication process or of semiconductor structure fabricated thereby. Features in the data set being discernable to an extent limited by a data resolution. The memory circuitry also stores a machine-learning model comprising parameters having respective values assigned thereto as constrained by a model training process. The machine-learning model being a pyramidal residual convolutional neural network. The memory circuitry further includes a training data set containing features that are discernable to an extent limited by a training resolution that is greater than the data resolution, the training data set comprising the electromagnetic spectral data acquired from the spectrometer. The apparatus further includes processor circuitry communicatively coupled to the memory circuitry and that generates an output data set from the data set in accordance with the machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set. The rough spectrometer has a rough slit, the detailed spectrometer has a detailed slit that includes an opening that is smaller than a corresponding opening of the rough slit, and the training data set includes low resolution training data that are generated by the rough spectrometer and high resolution training data that are generated by the detailed spectrometer.

[007b] According to a third aspect of the present invention, there is provided a system for processing material for semiconductor fabrication. The system includes a chamber in which the materials are contained. The chamber includes a port through which the semiconductor fabrication processing is monitored. The system also includes a data acquisition instrument communicatively coupled to the port of the chamber and that generates a data set indicative of a state of the semiconductor fabrication process. Features in the data set being discernable to an extent limited by a data resolution of the data acquisition instrument. The data acquisition instrument is a spectrometer that generates electromagnetic spectral data as the data set. The system further includes processor circuitry communicatively coupled to the data acquisition instrument and that generates an output data set from the data set in accordance with a machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set, the machine-learning model being a pyramidal residual convolutional neural network and including parameters having respective values assigned thereto as constrained by a model training process.

the spectrometer includes an entrance slit and a grating, the training data set includes low resolution training data and high resolution training data that are acquired from the spectrometer, and the grating is located closer to the slit when the low resolution training data are acquired than when the high resolution training data are acquired.

BRIEF DESCRIPTION OF THE DRAWINGS

[008] FIG. 1 is a schematic block diagram of an example system in which the present inventive concept can be embodied.

[009] FIG. 2 is a schematic diagram of an artificial neural network (ANN) by which the present invention can be embodied.

[0010] FIG. 3 is a schematic diagram of an example spectrometer with which the present invention can be embodied.

[0011] FIG. 4 is a schematic diagram of a spectrometer entrance slit and an image 420 thereof for simulating data in embodiments of the present invention.

[0012] FIG. 5 is a graph of low resolution spectral data for underfill and overfill implementations of low resolution spectrometers used in embodiments of the present invention.

[0013] FIG. 6 is a graph of high resolution spectral data for underfill and overfill implementations of high resolution spectrometers used in embodiments of the present invention.

CLAIMS

1. An apparatus comprising:

a data acquisition instrument that observes a state of a semiconductor fabrication process and generates a data set accordingly, wherein the data acquisition instrument is a spectrometer that generates electromagnetic spectral data as the data set;

memory circuitry that stores:

the data set indicative of the state of the semiconductor fabrication process or of semiconductor structure fabricated thereby, features in the data set being discernable to an extent limited by a data resolution;

a machine-learning model comprising parameters having respective values assigned thereto as constrained by a model training process, the machine-learning model being a pyramidal residual convolutional neural network; and

a training data set containing features that are discernable to an extent limited by a training resolution that is greater than the data resolution; and

processor circuitry communicatively coupled to the memory circuitry and that:

generates an output data set from the data set in accordance with the machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set,

wherein the spectrometer includes an entrance slit and a grating, the training data set includes low resolution training data and high resolution training data that are acquired from the spectrometer, and the grating is located closer to the slit when the low resolution training data are acquired than when the high resolution training data are acquired.

2. The apparatus of claim 1, wherein each functional block includes a plurality of convolutional layers that convolve corresponding ones of the parameters with a feature map based on the data set.

3. The apparatus of claim 2, wherein each functional block includes a plurality of activation layers that limits passage of the convolved feature map to a subsequent layer in the functional block in accordance with an activation function.

4. The apparatus of claim 3, wherein the activation function is a rectified linear unit activation function.

5. The apparatus of claim 1, wherein the processor circuitry implements a process controller by which the semiconductor fabrication process is controlled based on the output data set.

6. The apparatus of claim 1, wherein the training data set comprises spectral data acquired from the spectrometer.

7. An apparatus comprising:

a data acquisition instrument that observes a state of a semiconductor fabrication process and generates a data set accordingly, wherein the data acquisition instrument includes a rough spectrometer and a detailed spectrometer that generate electromagnetic spectral data as the data set;

memory circuitry that stores:

the data set indicative of the state of the semiconductor fabrication process or of semiconductor structure fabricated thereby, features in the data set being discernable to an extent limited by a data resolution;

a machine-learning model comprising parameters having respective values assigned thereto as constrained by a model training process, the machine-learning model being a pyramidal residual convolutional neural network; and

a training data set containing features that are discernable to an extent limited by a training resolution that is greater than the data resolution, the training data set comprising the electromagnetic spectral data acquired from the spectrometer;

processor circuitry communicatively coupled to the memory circuitry and that:

generates an output data set from the data set in accordance with the machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set,

wherein the rough spectrometer has a rough slit, the detailed spectrometer has a detailed slit that includes an opening that is smaller than a corresponding opening of the rough slit, and the training data set includes low resolution training data that are generated by the rough spectrometer and high resolution training data that are generated by the detailed spectrometer.

8. A system for processing material for semiconductor fabrication comprising:

a chamber in which the materials are contained, the chamber including a port through which the semiconductor fabrication processing is monitored;

a data acquisition instrument communicatively coupled to the port of the chamber and that generates a data set indicative of a state of the semiconductor fabrication process, features in the data set being discernable to an extent limited by a data resolution of the data acquisition instrument, wherein the data acquisition instrument is a spectrometer that generates electromagnetic spectral data as the data set; and

processor circuitry communicatively coupled to the data acquisition instrument and that generates an output data set from the data set in accordance with a machine-learning model such that features in the output data set are discernable to an extent limited by an output data resolution that is finer than the data resolution of the data set, the machine-learning model being a pyramidal residual convolutional neural network and comprising parameters having respective values assigned thereto as constrained by a model training process, wherein the spectrometer includes an entrance slit and a grating, the training data set includes low resolution training data and high resolution training data that are acquired from the spectrometer, and the grating is located closer to the slit when the low resolution training data are acquired than when the high resolution training data are acquired.

9. The system of claim 8, wherein the spectrometer is optically coupled to the port of the chamber and generates spectra as the data set, an other data set being high resolution spectra having a finer resolution than that generated by the spectrometer, the spectrometer having a physical design that is characterized by a bandwidth and an optical throughput that are not diminished by way of processing the spectra by the machine-learning model.

10. The system of claim 9, wherein the spectrometer includes the entrance slit and a detector array that define the bandwidth and the optical throughput.

11. The system of claim 8, wherein the training data set includes the spectral data acquired while a distance between the entrance slit and the detector array is varied.

12. The system of claim 9, wherein the process controller analyzes the high resolution spectra to determine the state of the semiconductor fabrication process and generates control signals that modify the semiconductor fabrication process to compel a different state thereof.