# Color-coded display of information in scanning electron microscopy

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This article describes a system for color-coding of images for qualitative and quantitative analysis of information in the scanning electron microscope. The method is based on an "intensity-color" conversion, which matches a certain color with a certain parameter or property of the object. The video signal is quantized with respect to the color spectrum in the secondary-electron-emission, back-scattered-electron, elemental-analysis, potential-contrast, and induced-current modes in studying semiconductor structures. The potentialities of color-coding of the video signal are demonstrated experimentally in fast quality control of microelectronic parts and in determining the local distribution of chemical elements in materials under study.

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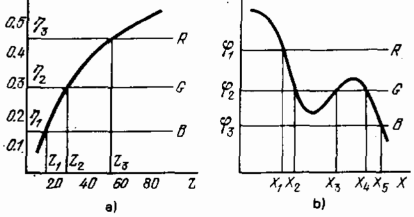
By using the scanning electron microscope (SEM) one can obtain varied information on the structure and physical properties of an object.[1-3] In particular, the SEM enables local elemental analysis of the material. The qualitative or quantitative analysis of the distribution of chemical elements having different atomic numbers is mainly performed in the x-ray emission, and cathodoluminescence modes, and also by recording backscattered and Auger electrons. However, it is practically impossible in a black-white display to identify in the back-scattered electrons elements with slightly differing atomic numbers $Z$, since the human eye can distinguish no more than 16 gradations of black-white imaging.

We have applied the principle of color-coding[1,4-6] in the present work for studying the local properties and structure of the surface of an object, since the number of information-bearing colors and shades distinguishable by the eye can be two or three orders of magnitude larger than in black-white perception. Moreover, in qualitative analysis in a back-scattered-electron (BSE) mode, we have employed a modified binary BSE detector. In combination with color coding of the video signal, it has enabled us to perform a functional comparative analysis with maximal spatial resolution, relatively high sensitivity, and great reliability.[6]

In principle, any information-bearing signal in the SEM can be subjected to artificial "coloring", and here the color contrast improves visual perception and facilitates interpretation of images.[6-9] The following method is the general principle of color coding. One "quantizes" the gray spectrum of the continuum of the video signal into the needed number of levels, to each of which one assigns a color by a previously adopted law or by arbitrary choice. For example, in studying an object in the BSE detection mode, one uses the fact that the reflection coefficient $\eta$ of the electrons, and thereby the intensity of the video signal, is determined by the atomic number $Z$ of the material being irradiated by the beam of high-energy electrons. The fraction $\eta$ of BSEs increases almost monotonically with increasing $Z$, as is demonstrated by the graph in Fig. 1a of the $\eta(Z)$ relationship for an energy of primary electrons $E_0 > 10$ keV.[2] This experimental graph corresponds rather well to the empirical relationship[3]: $\eta = -0.254 + 0.016\,Z - 0.000186\,Z^2 + 8.31 \times 10^{-7}\,Z^3$. According to the elementary theory of BSEs, this takes into account both single Rutherford scattering by the Coulomb field of the nucleus of the atom, and small-angle multiple scattering, in which an electron of the beam interacts with the electrons of the atoms of the object.

In ordinary recording of the BSE signal in the SEM, an element of high atomic number looks white on the screen, and one with low $Z$ black, while intermediate values correspond to various gradations of gray. Instead of developing densitometric curves or gradations of the gray image, it is more functional and accurate to perform the visual recognition and identification of the elements on the color screen of a monitor. The order of sequence of the colors fitting the value of $Z$ is established arbitrarily in each experiment in test specimens, in which a certain color is assigned to each $Z$. In this calibration the colors are usually chosen such that adjacent regions will show maximal color contrast in the image. The system enables one simultaneously to analyze up to 16 elements. However, in principle, one can increase this number by adding the appropriate number of level discriminators to the radioelectronic comparison circuit.

In Fig. 1a the signal intensity corresponds to the chemical element of atomic number $Z_1$ that is proportional to the reflection coefficient $\eta_1$, while it is arbitrarily "colored", e.g., blue ($B$), an element with the



a) b)

FIG. 1.

FIG. 3 (200×).

FIG. 4 (1000×).

FIG. 5 (500×).

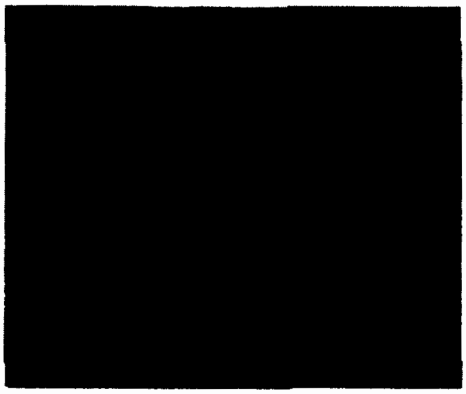


FIG. 6 (300×).

FIG. 7 (1000×).

FIG. 8 (300×).

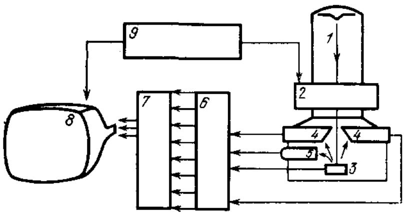


FIG. 2.

atomic number $Z_2$ is displayed as green ($G$), and the element with $Z_3$ red ($R$), etc.

If the video signal from the SEM bears quantitative information obtained by the appropriate metrological attachments and methods, then color coding enables one to display the distribution pattern of any characteristic parameter, e.g., lines of equal field intensity, the temperature distribution map, the potential relief at the surface, etc.

In the latter case, e.g., different values of the potential $\phi$ at the surface of a solid (semiconductor device) are marked with a certain color (Fig. 1b). The potential contrast is linearized by energy analysis of the secondary electrons using negative feedback in the frame scan.[10,11] This method enables one automatically to determine the magnitude of the potential $\phi_i$ at any coordinate $X_i$ and to assign any color to this value of $\phi_i$ (see Fig. 1b).

Figure 2 shows a simplified experimental system for color coding. The electron probe 1 of the SEM scans the specimen 3 with the aid of the deflecting coils 2. The BSEs are collected by two symmetric detectors 4, while the secondary electrons are caught by the collector-analyzer 5. The signals from the detectors as well as from the specimen are applied to the switching unit with multichannel comparators 6, where they are "quantized" into the appropriate number of gradations. In the color-coding matrix 7 a color is assigned to each interval of gradations. The output signals are applied to the color monitor 8, which is scan-synchronized with the SEM by the apparatus 9.

As we have noted above, one can perform rapid elemental analysis of specimens with a pairwise symmetric BSE detector system (with summation of the signals from both detectors). This considerably suppresses the effect of the topography of the surface. Elemental analysis can be performed with a spatial resolution of a fraction of a micrometer and with an atomic-number resolution $\Delta Z = 1$ (for elements in the range $Z = 4$–$30$), $\Delta Z = 2$ ($Z = 30$–$60$), and $\Delta Z \geqslant 3$ for $Z > 60$. This unevenness in the resolution $\Delta Z$ stems from the fact that the difference in the reflection coefficient $\eta$ declines with increasing $Z$ for a fixed value of $\Delta Z$ (see Fig. 1a).

As an illustration, Fig. 3 (color insert) shows a color-coded image of a silicon-metal junction, where the following components are sharply distinguished: nickel (green), copper (blue), silicon (red), and tin (yellow). In this case good atomic-number resolution $\Delta Z = 1$ is demonstrated between Ni ($Z = 28$) and Cu ($Z = 29$), which are indistinguishable on an ordinary black-white monitor screen. The scale marker and the elements being analyzed are indicated in the symbol field in the upper left corner of the picture.

The intermetallic intermediate layer and diffusional porosity in a soldered seam are well distinguished in Fig. 4, which shows the microstructure of the joint between a Kovar cover (blue) with the base of the body of an integrated circuit (green) made with a solder with a high content of tin (red).

An image of the ground joint of a thyristor structure is shown in Fig. 5, where we can see the following elements: Mo—green, Fe—red, Si—blue.

Figure 6 illustrates inhomogeneity of the oxide coating and the metallization bars in a defective integral circuit. Here the green color corresponds to the surface metallization, and blue to the interlayer insulation. Well marked in this picture are the technical defects that arise from formation of spurs and breaks in the metallization bars, which is a potential cause of breakdown, short-circuits, and failures of circuits in operation. Images similar to that shown in Fig. 6 open up great potentialities in automation of visual analysis of the topology of integrated circuits, since they allow one operationally to establish the distribution of materials in the prepared structure from their "colors". Moreover, the image of each fragment (distribution of elements or parameters) can be separately monitored by color matching with a reference structure.

Application of a color-coding system enables visual monitoring of the quality of not only passive elements (see Fig. 6), but also active elements of semiconductor devices. Thus, Fig. 7 shows a foreign inclusion ($SiO_2$ precipitate—red) in a plane $p$-$n$ junction of a phototransducer (blue). The image was obtained in the induced-current mode. The green aureole around the defect structure probably arises from the lateral field formed by the concentration gradient of the impurity decorating the precipitate complex.

Figure 8 shows the potential contrast of an integrated circuit taken in the secondary-electron-emission mode with color-coding of the electric microfields. Here the red, green, light blue, and yellow colors display the distribution of different potentials $\phi$, for which the color-coding principle is explained in Fig. 1b.

Experimental test has shown a rather high effectiveness and universality of the principle of color-coding for displaying varied information in the SEM. The spatial resolution in elemental-composition analysis in the BSE mode with color-coding is greater than in x-ray structural and cathodoluminescence analyses. The signal/noise ratio in visualizing structures of low atomic number is also greater. In principle, qualitative analysis using color-coding in the BSE mode can supplement well the quantitative x-ray analysis, especially in visualizing the distribution of light elements.

As regards displaying defined levels of equal signal in pictures—isolines—color-coding allows quantitative mapping of the object parameters being studied.

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