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Some basic mineralogical and electrophysical characteristics affecting auriferous pyrite and arsenopyrite flotation

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ABSTRACT

Pyrite and arsenopyrite are the main mineral concentrators of gold. The presence of interstitial gold in the pyrite and arsenopyrite crystal lattice results in the formation of structural defects that cause significant changes and variations in the electrophysical characteristics of the minerals. Beside gold content and the nature of its dissemination, pyrites and arsenopyrites from gold ore deposits are characterized by a rich spectrum of impurity species, with generally above average relative abundance of Au, Ag, Cu, Pb, Zn and As. The presence of these isomorphous impurities in pyrite and the non-stoichiometry of the major pyrite components (Fe and S) are responsible for the variability of semiconducting, electrophysical and flotation properties of this mineral.

The mineralogical peculiarities and electrophysical characteristics of auriferous pyrites and arsenopyrites from several gold deposits were examined and correlation between element composition, mineral electrode potential, electrical resistivity, termal electromotive force coefficients and their flotation properties has been revealed. The role of isomorphous impurities in the formation of hydrophobic sulfhydric collector layers on mineral surfaces in complex ore processing has been elucidated. The parameters characterizing the variability of the Fe:S ratio in pyrite of different origin have been determined based on non-stoichiometry characteristics of natural gold-bearing sulfide crystals. It has been found that pyrites non-stoichiometric composition correlates with the collector chemisorption on their surface. © 2003 SDU. All rights reserved.

Keywords: Flotation; Pyrite; Arsenopyrite; Gold

1. INTRODUCTION

Gold-sulfide ores consisting essentially of pyrite, arsenopyrite, chalcopyrite and pyrrhotite become one of the major precious metal sources, being presently estimated to account for more than 40% of total world gold reserves. In addition, much consideration is being given to urgent issues of gold recovery from base metal ores and old tailings from past operations.

The majority of Russian gold deposits, while with considerable explored reserves, are characterized by a moderate average gold content of ores (mostly 5-10ppm Au), in addition, with quite irregular gold distribution and widely varying processing characteristics of gold-bearing ores. Environmental (weather and climatic) conditions characterizing the localities of these deposits are usually unfavorable for the employment of geotechnological processing techniques like heap leaching. The co-presence of pyrite and arsenopyrite (with arsenopyrite accounting for up to 50% of total sulfide) in most of the ores hampers ore processing by flotation because of strict limits on As content of flotation concentrates, and practically precludes the use of any pyrometallurgical methods. Both new ores of this sort and concentrates produced from them by traditional methods are classified as "resistant" products, with most of their hosted gold contained within solid mineral aggregates. The proportion of "cyanidable" gold in these products never exceeds 35%.

The prime objective of flotation of gold-bearing sulfide minerals is to increase precious metal recovery and to reduce the product cost through achieving maximum selectivity of the separation process. Separation of Fe and As sulfides in selective flotation of gold-bearing ore products helps reduce the amount of ore mass being sent to hydrometallurgical processing, and permits of recovering gold from As-free gold-containing pyrite concentrate by using a lower-cost pyrometallurgical procedure.

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The presence of interstitial gold in the pyrite crystal lattice results in the formation of structural defects, increase in As content, and creation of acceptor sulfide vacancies (Tauson *et al.*, 1996). This causes significant changes and variations in the electrophysical characteristics of the minerals being studied. Even within a common mineral assemblage, resistivity and thermal electromotive force coefficient values may vary very widely, up to conductivity sign reversal due to the formation of "blocking zones".

The problem of auriferous arsenopyrite and pyrite separation under gold arsenic ores flotation is connected as with similarity of technological characteristics of separated mineral components, so and irregularity of element composition and electrophysical features of one and the same mineral from various deposits and even from different areas of the same deposit.

The comparative analysis of crystal-structural and electrophysical properties of pyrite and arsenopyrite (Shuey, 1975; Rakcheev, 1989; Urusov *et al.*, 1997) identified the following differences (Table 1). The values of specific resistance and coefficient of thermo-electromotive force of pyrite vary in broader range of meanings than for arsenopyrite. Fe-Fe bond length in pyrite is half as large than in arsenopyrite. Current carrier mobility in pyrite is 3-5 times higher than in arsenopyrite. Fe-S bond in pyrite is more polaric and features the displacement of electrons to anion.

Table 1
Crystal-structural and electrophysical properties of pyrite and arsenopyrite

Characteristics	Pyrite	Arsenopyrite
ρ, Ohm.m	$10^{-5} - 10^{-1}$	$10^{-5} - 10^{-3}$
α_{TEMF}, μV/°C	-300 - +500	100 – 300
Bond length, A	Fe-S – 2.26	Fe-S – 2.25
	S-S – 3.66	Fe-As – 2.35
	Fe-Fe – 3.81	As-S – 2.33
		Fe-Fe – 2.9
Chemical formula	$Fe^{2+}(S_2)^{2-}$	$Fe^{3+}(AsS)^{3-}$
Activating energy, eV	1.2 – 0.77	0.067 – 0.075
Energetic barrier, eV	0.9	0.2
Current carriers mobility, $sm^2.V^{-1}.s^{-1}$	0.5 – 3.0	0.1 – 1.0
Non-stoichiometry	S/Fe – 1.94 – 2.01	S/Me – 0.5; S/As – 1.0
Isomorphous impurities	Co, Ni, As, Zn, Cu	Co, Ni, Sb
Fe-S bond polaric characteristic, λ	0.76	0.65
Effective formula	$Fe^{+0.68}$	$Fe^{+0.72}$
	$S^{-0.34}$	$As^{-0.27}$
		$S^{-0.45}$

As it is determined by Korobeynikov *et al.* (1993), a rich spectrum of impurity species, with generally above average relative abundance of Au, Ag, Cu, Pb, Zn and As, all of these impurities showing a significant dispersion of statistical parameters. Co, Ni and Cu are donor admixtures, while, As is the most frequent acceptor impurity. In arsenopyrite the deficit of arsenic causes n-type conductivity, but for arsenic enriches samples transition to p-type is observed.

To summarize, structural imperfections are considered to be the basic factors effecting the variabilities of semi-conducting and physical characteristics of natural pyrites and arsenopyrites. Isomorphous inclusions of gold and other impurities in mineral lattice and the non-stoichiometry of the major mineral components (for example, iron and sulfur in pyrite) are responsible for the structural defects formation.

The location of sulfur atoms on cells panes and ribs in pyrite makes it accessible to oxygen attachment. In arsenopyrite sulfur atoms are located inside the crystal lattice, and so iron and arsenic atoms shield them. Due to these crystal peculiarities, pyrite generally exibites higher redox reactivity in flotation pulp than arsenopyrite. But under traditional sulfide flotation processing these minerals often reveal similar technological recovery. Arsenopyrite floatability has also appeared to be affected by isomorphous admixture composition (Plaksin *et al.*, 1955). In order to produce high-grade pyrite concentrate (less than 2% As) effective flotation conditions should be worked out.

Examination of the composition of surficial compounds forming on the surface of pyrite during its flotation revealed that dixanthogen is the main form of xanthate sorption on pyrite, with no consensus existing now among researchers as to the presence and formation conditions of metal xanthate compounds (Avdokhin and Abramov, 1989; Leppinen *et al.*, 1995; Bradshaw and O'Connor, 1997).

The main objective of this study was to examine the electrophysical and crystal-structural properties of Fe and As sulfides and to develop a methodology for the assessment of mineralogical and processing characteristics of pyrite and arsenopyrite with differing genesis. The developed method is proposed to identify the essential factors governing the behavior of minerals during flotation and to select proper criteria of Fe and As sulfides selective flotation in refractory gold ore processing.

2. EXPERIMENTAL

Pyrite and arsenopyrite samples from several deposits of Russia and CIS countries were studied (Chanturiya *et al.*, 1998). The chemical composition of the specimens was determined by spectral analysis using a LMA laser spectral microanalyzer, and thereafter checked by atomic absorption tests made with decomposed mineral samples attacked by aqua regis. The phase composition of the specimens was studied using a DRON-3 X-ray diffractometer, with the ASTRA software package used to reference the spectral bands. Surface characteristics of the minerals were analyzed using an Infarm-I infrared microscope. The electrophysical properties of the minerals, namely, their electrical resistivity (ρ), thermal electromotive force coefficient (α_{TEMF}) and conductivity type, were examined using the standard techniques (Shuey, 1975) by testing polished sections of the specimens. Hall constant (R_H) values and charge carrier concentrations (n_e or n_p) were calculated.

The electric potentials of monomineralic electrodes (E) were measured in environments with pH varying between 5 and 12, having selected the least jointy zones in the initial mineral specimens. In each of the electrode tests, the electrode consisted of a holder designed as a glass tube 10mm in diameter, with a monomineralic tablet mounted (cemented by epoxy resin) at one of the ends and a low-resistance wire soldered to the tablet. The outer end of the wire was connected directly to the measuring bus of the meter (an I-130 ionometer operating in a millivoltmeter mode). For ease of mounting in the glass holder, the monomineralic tablet was cone-shaped, 8mm across end 6 to 12mm thick. The inner conductor consisted of a copper wire 0.7mm thick. To ensure high contact conductivity, a copper layer was sprayed onto the mineral surface, whereafter a copper conductor was soldered to the sprayed contact layer. Spraying was performed by the thermal vacuum method, in a specially designed vacuum station, during 30 minutes. The monomineralic electrode potential was measured in reference to an AgCl electrode with subsequent conversion with respect to a saturated hydrogen electrode (SHE) by the following formula:

$$E_{SHE} = E_{AgCl} + 201 mV \tag{1}$$

The true formulae of pyrites and non-stoichiometry of anionic (sulfide) part were calculated from analytical ratio of iron and sulfur (Chanturiya *et al.*, 2000).

The amounts of elementary sulfur and adsorbed butyl xanthate compounds under certain pH values were analyzed by the extractive UV-spectrophotometric analysis on Specord M 40.

Flotation and sorption tests were performed on 1g samples ground to -100+63μm, with flotation volume of 20ml, xanthate dosage 300g/t, frother dosage 150g/t, conditioning and flotation time taken to be 2min with each reagent.

3. RESULTS AND DISCUSSION

Impurity content of the samples representing different monomineralic pyrite varieties changes as follows: 0.14% to 3.2% Cu, 0.04% to 2% Ni (both are donor impurities), and 0.01% to 2.5% As (acceptor impurity), gold content varies from 1 to 40ppm Au (Tables 2 and 4). Arsenopyrite samples contain the following impurities: 0.04% to 0.1% Cu and less than 0.01% Ni, with gold content varying between 1 and 100ppm. Pyrite admixture composition varies much more widely than that of arsenopyrite, which is reflected in semi-conductive properties of monomineralic species being studied (Tables 3 and 4).

Table 2
Elemental composition and non-stoichiometry of pyrite samples

| Sample | Content | | | | | | Real formula | Non-stoichiometry |
	Fe %	Sulfide S %	Cu %	As %	Au ppm	Surface mg/g S		(S/S$_{theoretic}$)
1	42.0	45.0	0.2	0.04	10	0.11	FeS$_{1.87}$	0.94
2	33.2	45.5	3.2	0.01	10	0.33	FeS$_{2..39}$	1.2
3	41.5	36.6	0.6	0.3	1	0.77	FeS$_{1.54}$	0.77
4	38. 3	33.8	0.8	2.5	40	0.23	FeS$_{1.55}$	0.78
5	38.7	45.5	0.14	0.1	10	0.19	FeS$_{2.05}$	1.03

Electrophysical characteristics studies have shown that electrical resistivity of the examined pyrite samples varies from 47.5×10^{-3} Ohm.m to 1266×10^{-3} Ohm.m, and their TEMF coefficient varies between 100 and 476μV/°C. For arsenopyrite samples, these parameters vary as follows: $(11-130) \times 10^{-3}$ Ohm.m and 115-180μV/°C, respectively. Pyrite samples (1) and (2) are characterized by a predominance of n-type conductivity, while in pyrite samples (3), (4) and (5) the conductivity is essentially p-type, much like in arsenopyrite samples (6), (7) and (9), and only arsenopyrite sample (8) demonstrates a combined type of

conductivity. All pyrite samples with predominantly n-type conductivity have nearly the same Hall constant and charge carrier concentration values, whereas in pyrite with p-type conductivity the scatter of these parameters is as great as 1-1.5 orders of magnitude. The increase in pyrite gold content from 10 to 40ppm results in TEMF coefficient rising from 100 to 467μV/°C. Arsenopyrite (9) with 1ppm Au content is characterized by α_{TEMF} =120μV/°C.

Table 3
Electrophysical characteristics of pyrite samples

Sample	Electrical resistivity, $\times 10^{-3}$, Ohm.m	TEMF cofficient, μV/°C	Sign of TEMF	Hall constant, $\times 10^{-6}$, m^3/C	Type of conductivity	Current carriers concentration, $\times 10^{23}$, m^{-3}
1	181	100	-	-10.1	n	62
2	124	240	-	-10	n	62.5
3	1266	-	+	+135.2	p	4.6
4	204	476	+	+47.3	p	13
5	47.5	153	+	+4.2	p	148

Table 4
Element composition and electrophysical characteristics of arsenopyrite samples

Sample	Content			Surface mg/g S	Electrical resistivity, $\times 10^{-3}$, Ohm.m	TEMF coefficient, μV/°C	Sign of TEMF
	As %	Cu %	Au ppm				
6	36.2	0.06	100	5.8	11	115	+
7	21.4	0.04	10	26.6	41	180	-
8	29.1	-	10	31.7	130	164	+ or -
9	39.8	0.1	1	57.6	78	120	+

From analysis of experimental results and their correlation data from literature on mineralogy of gold deposits (Korobeynikov *et al.*, 1993) it was concluded that the pyrite and arsenopyrite samples selected for testing in this study were representative enough to adequately reflect the diverse mineralogy of pyrite-arsenic ores.

Using the data presented in Table 2, the limiting degree of pyrite oxidation was determined with which the relationships between the impurity content, semiconducting, electrochemical and processing characteristics of pyrite can still be analyzed with enough certainty. To do this, the dependence of formatted resistivity values on free sulfur concentration on mineral surfaces was examined. This relationship, generally formulated as ρ/ρ_{max}=f(S/S$_{max}$), proved to be a second-degree polynomial with R^2>0.9, showing an intensively ascending branch for argument values greater than 0.66. From this reasoning, the maximum admissible amount of elemental sulfur that still does not affect the remaining mutual correlations was taken to be <1.6 x 10^{-8}mole/kg, and only those pyrite samples that satisfied this condition were then dealt with in subsequent experiments.

The experimental E vs. pH curves plotted in Figure 1 for pH + 5-12 are described by second-degree polynomial with a quite high square correlation coefficient (R^2> 0.98). The numbers of the curves in Figure 1 correspond to the numbers of the analyzed mineral samples. Pyrite samples with n-type conductivity (curves 1 and 2) show peak potential values (E$_{max}$) equal to 394 and 371mV, respectively, both extreme max points corresponding to pH=8. Pyrite samples with a predominance of p-type conductivity (curves 4 and 5) are characterized by E$_{max}$ values of 301 and 234mV, respectively, with both extreme points shifted by 1-1.5 pH units towards higher acidity relative to those of samples 1 and 2. Lastly, the peak values of arsenopyrite electrode potentials are equal to 252mV (curves 6 and 9) and 263mV (curve 8), the extreme points corresponding to pH=7 and pH=6.

To formalize the experimental data, the electrode potential values in the descending segments of functional relationships were formatted through division by E$_{max}$ values determined for respective monomineralic electrodes. Figure 2 displays the E/E$_{max}$ vs. pH linear approximation plots for decreasing potential values measured without (curves 1 - 5, a) and with (curves 1-5, b) sodium buthylxanthate. Dashed lines depict the calculated E/E$_{max}$=f(pH) relationships corresponding to pyrite oxidation without any sulfhydric collector yielding ferric iron hydroxide and free sulfur (curve 10, a) and to pyrite oxidation with added xanthate reflecting the stage of dixanthogen formation (curve 10, b).

Currentless potential values of pyrites with p-type conductivity (4 and 5) are nearly identical to the values calculated for the process of formation of a Fe(OH)$_3$ phase on mineral surfaces, whereas the

potentials of samples with n-type conductivity (1 and 2) are 100-150mV higher, which appears to be evidence of preferential dissolution of surficial films on pyrites with n-type conductivity. Measurements of monomineralic electrode potentials in the presence of sodium buthylxanthate revealed evidently preferential xanthate oxidation to dixanthogen on the surfaces of samples with n-type conductivity. Potential values measured for pyrites with p-type conductivity (4) are close to the value obtained for arsenopyrite (9).
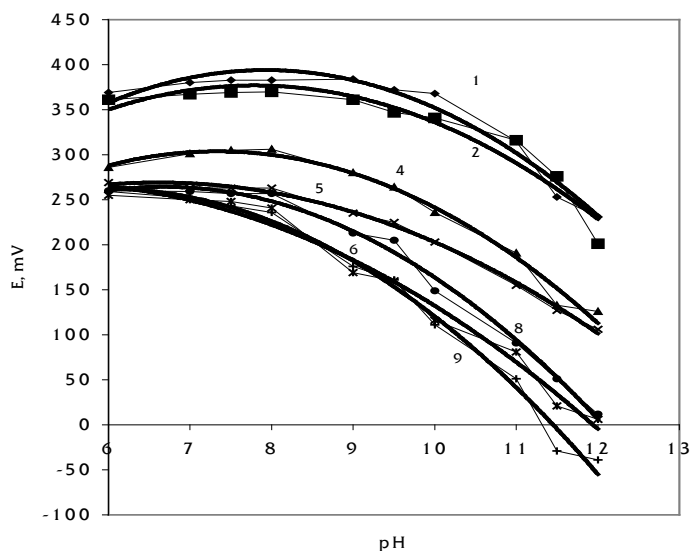
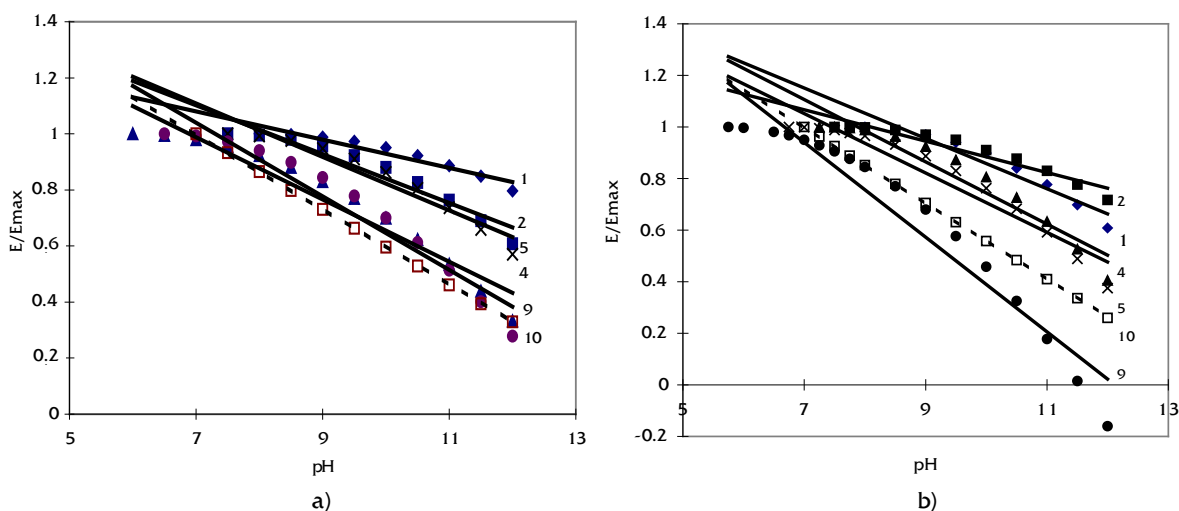Figure 1. Mineral electrode potential as a function of pH

Figure 2. Formatting mineral electrode potential as a function of pH
a) without buthylxanthate; b) with buthylxanthate addition

Analysis of products of xanthate reaction with pyrite and arsenopyrite under varying pH conditions revealed a correlation between the nature and concentration of impurity species and the amount of xanthate compounds on sample surfaces and in the liquid phase of monomineralic suspensions.

Figure 3 shows dixanthogen sorption plotted versus pH for all the mineral samples tested, with numbers of curves corresponding to sample numbers in Tables 2 and 4. The study revealed that, in monomineralic suspensions of essentially pure Fe and As sulfides, xanthate is oxidized to dixanthogen. Experiments on samples with Cu, Au and Ni impurities showed the emergence of metal xanthates, the proportion of which in overall sorption of the collector increases with increasing impurity content of the samples. Generally, pH for pH, the overall xanthate sorption environment to an alkaline one. Xanthate sorption on arsenopyrite ceases at pH higher than 10, whereas for pyrite xanthate sorption terminates at pH higher than 11-12.
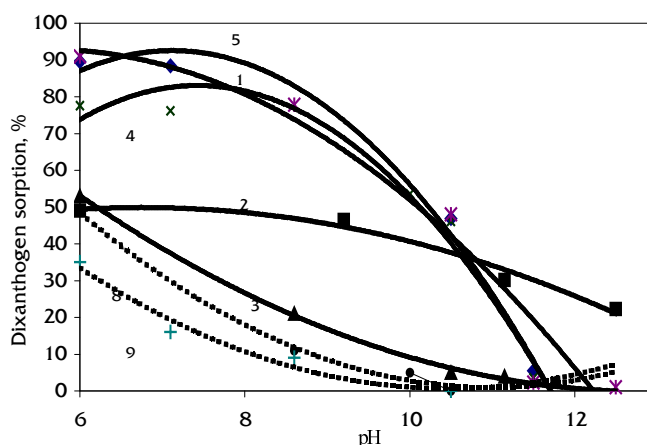
Figure 3. Dixanthogen sorption as a function of pH
(Numbers of curves correspond to pyrite and arsenopyrite samples in Tables 2 and 4)

All natural auriferous pyrites are found to be of non-stoichiometric composition (Table 2).

As of now, three different trends are evident in theories of non-stoichometry of crystalline substances, which can be generally classified as chemical, physicochemical and crystallochemical approaches (Anderson, 1975). Non-stoichiometry is sometimes treated as some disbalance between the anion and cation concentrations in a crystal, or as the presence of lattice vacancies making for thermodynamic stability of a crystalline substance. From the standpoint of structural crystallochemistry, non-stoichiometry may be related to some displacement of primary structure microblocks or to intergrowth of structurally similar microdomains with differing composition (Fender, 1972). Anyway, non-stoichiometry is relevant to quantitative relationships between different components of a crystalline substance. In more exact terms, a mineral with the formula M_aX_b must have a constant a/b ratio (the ratio between the quantities of lattice nodes occupied by M and S atoms) to be stoichiometric, and with a variable a/b ratio the mineral would be non-stoichiometric.

When dealing with non-stoichiometric crystals, the character and, in some cases, the degree of deviation from stoichiometry may be indicative of mineral acidity/alkalinity, even within a common mineral species, as both conductivity type and actual electrochemical potential of a mineral do depend on its composition. For example, pyrite with formula $FeS_{1,96}$ will have n-type conductivity and higher alkalinity as compared to $FeS_{2,04}$ pyrite, which will be characterized by a deficiency of the cationic part of pyrite mineral formula. The formulae of these two pyrites would be more correctly written taking into account the presence of anionic/cationic vacancies and respective charges that counterbalance the excessive charge in cationic/anionic parts of the mineral formulae: $Fe^{2+}[\ ]^{-0,04}S_{1,96}^{-1,96}$ and $Fe^{2+}[\ ]^{+0,04}S_{2,04}^{-2,04}$. Only in this case will the universal principle of electric neutrality of actual solids be obeyed. At room and higher temperatures, the electrons that counterbalance the excessive positive charge in the first pyrite variety mostly rest in a quasi-free state within the conduction band, and quasi-free positive holes form in the valence band of the second pyrite. In particular cases, knowledge of the sign of TEMF for the minerals occurring in association would suffice for reliable comparative assessment of their acidity/alkalinity characteristics.

Based on analysis of the essential characteristics of the examined samples, the pyrites studied were classified by the character of relationships between the structure and composition, as is customary when studying nonstoichiometric compounds (Wadsley, 1964). The deviation from multiplicity in the cationic-to-anionic rations in samples (1) and (5) is respectively due to the lack of variable S and Fe amounts (subtraction). Non-stoichiometry of samples (2) and (4) may be related to the advent of impurity elements (respectively, Cu and As) into the host mineral lattice (interpolation). Lastly, sample (3) with high free sulfur content is characterized by a peculiar type of replacement, where some excessive Fe atoms occupy the sites that were previously occupied by sulfur and became vacant owing to S^{2-} oxidation to S^0.

The comparison of the data on the ratio of actual and stoichiometric sulfide sulfur contents ($S/S_{theoretic}$) and the elemental sulfur amounts on their surfaces demonstrated the relationship between the non-stoichiometric factor and mineral oxidizing abilities. In particular, on pyrite surfaces (1) and (5) with a small deflection from a stoichiometry 0.11 and 0.19mg/g of free sulfur is determined, while on samples with a considerable excess (2) or deficit (3) of anionic parts – 0.33 and 0.77mg/g of elemental sulfur, accordingly. It should be noted that pyrite gold content effects its surficial oxidation. Samples (3) (1ppm Au) and (4) (40ppm Au) are characterized by approximately identical deviation from a stoichiometric sulfide sulfur content, however free sulfur amount determined on auriferous sample surface is 3 times less than on sample (3).

The deviation of pyrite formula from the stoichiometric Fe:S ratio resulting in the formation of cationic and anionic vacancies is evidence of partial destruction of pyrite crystal lattice, that has appeared to effect the forms of xanthate adsorption on the mineral surface. The dependence of the proportion of chemically adsorbed collector on the ratio of the actual and theoretical sulfide sulfur content of the sample is illustrated by Figure 2. Increase in non-stoichiometry, both towards the excess of the anionic part of the mineral formula and towards its deficiency, evidently tends to increase the proportion of chemisorption.

The relationship between chemisorbed form of collector and a proportion of a substantial and idealized content of sulfide sulfur is illustrated by curves in Figure 4. The increasing in non-stoichiometry as in a form of anionic part surplus or its shortage results in the chemical sorption ascending.
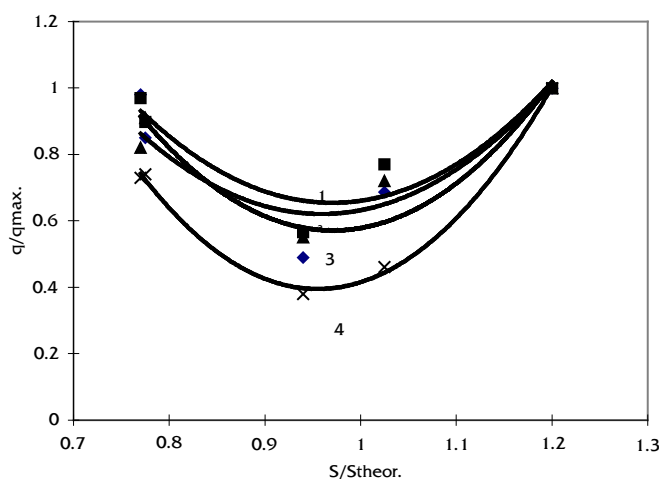

Figure 4. Xanthate chemisorption as a function of pyrites anionic part non-stoichiometry
(1 – pH 9; 2 – pH 10; 3 – pH 11; 4 – pH 12)

From the data on a free sulfur amount and its stability on the mineral surfaces, and also magnitude of the collector chemisorption it is possible to suspect, that samples with failure of iron and sulfur ration multiplicity aroused by the entrance of elements-admixtures in the lattice of mineral-master, will differ on the behavior in flotation process.

Analysis of pyrite and arsenopyrite floatability plotted versus pH (Figure 5) reveals that samples (1) and (5) have quite similar flotation properties. For these pyrite samples, recovery ranges up to 80% with pH varying between 9 and 11. Further increase in pH results in partial depression, such that with pH varying between 12.0 and 12.2 pyrite recovery does not exceed 25%. Pyrite samples (2) and (4) with high Cu, As and Au contents are readily floatable even in a highly alkaline environment with pH as high as 11.8-12.2. Pure arsenopyrite samples (7) and (8) are most sensitive to depressive action of the alkaline medium.
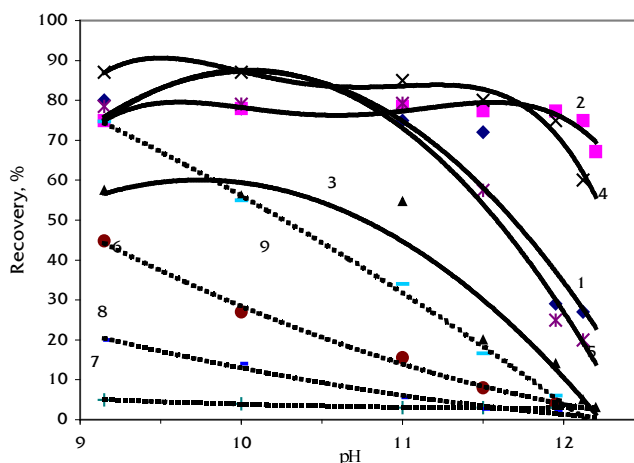

Figure 5. Floatabilities of pyrite and arsenopyrite samples as a function of pH
(Numbers of curves correspond to pyrite and arsenopyrite samples in Tables 2 and 4)

The method of correlation analysis involving the principle of formalization of experimental relationships was used to derive the linear correlation equations linking the impurity contents, TEMF coefficients, non-stoichiometry factors and pyrite and arsenopyrite recovery values (Table 5).

The study revealed a positive liner correlation between formatted values of pyrite electrode potential at neutral pH and electrical resistivity (R^2=0.91). There is a positive liner correlation between electrical resistivity and copper impurity content of arsenopyrite (R^2=0.97). The fact that no correlation was found between electrical resistivity and impurity content of the analyzed pyrite samples is, in our opinion, related to joint participation of donor and acceptor impurity species in electrical resistivity of the pyrites being studied.

Table 5
Linear correlatios between the characteristics of different pyrite and arsenopyrite varieties

Nr	Function	Argument	R^2	Constraints providing for linear approximation certainty
		Pyrite		
1	E/E_{max}	ρ/ρ_{max}	0.91	pH=6-8
2	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	$\alpha_{As}/\alpha_{As\ max}$	0.98	$0.01\% < \alpha_{As} < 2.5\%$
3	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	$\alpha_{Au}/\alpha_{Au\ max}$	0.88	$0.002\% < \alpha_{Au} < 0.01\%$
4	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	$\alpha_{Ni}/\alpha_{Ni\ max}$	0.85	$0.015\% < \alpha_{Ni} < 1.5\%$
5	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	$[S]/[S_{theor.}]$	0.92	pH=9-12
6	ρ/ρ_{max}	$[S]/[S_{theor.}]$	0.91	pH=9-12
7	ρ/ρ_{max}	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	0.82	pH=9-12
8	$\varepsilon/\varepsilon_{max}$	$\alpha_{As}/\alpha_{As\ max}$	0.98	pH>10
9	$\varepsilon/\varepsilon_{max}$	$\alpha_{Ni}/\alpha_{Ni\ max}$	0.96	$0.015\% < \alpha_{Ni} < 1.5\%$, pH=6-7
10	$\varepsilon/\varepsilon_{max}$	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	0.94	$0.015\% < \alpha_{Ni} < 1.5\%$, pH=6-8
11	$\varepsilon/\varepsilon_{max}$	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	0.96	$0.01\% < \alpha_{As} < 2.5\%$, pH=10-12
		Arsenopyrite		
1	ρ/ρ_{max}	$\alpha_{Cu}/\alpha_{Cumax}$	0.95	$0.04\% < \alpha_{Cu} < 0.1\%$, pH=6-8
2	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	$\alpha_{Au}/\alpha_{Au\ max}$	0.96	$0.0001\% < \alpha_{Au} < 0.01\%$, pH=6-8
3	$\varepsilon/\varepsilon_{max}$	$\alpha_{TEMF}/\alpha_{TEMF\ max}$	0.91	$0.0001\% < \alpha_{Au} < 0.01\%$, $0.04\% < \alpha_{Cu} < 0.1\%$, pH=6-8

There is a positive linear correlation between α_{TEMF} and Au, As and Ni contents of the analyzed pyrite and arsenopyrite samples, with $0.002\% < \alpha_{Au} < 0.01\%$, $0.01\% < \alpha_{As} < 2.5\%$, and $0.015\% < \alpha_{Ni} < 1.5\%$. In addition, there was found a positive linear correlation between α_{TEMF} and pyrite non-stoichiometry ($[S]/[S_{theor.}]$) and a negative linear correlation between electrical resistivity and pyrite non-stoichiometry ($[S]/[S_{theor.}]$). In particular, with the use of pyrite non-stoichiometric parameter ($[S]/[S_{theor.}]$) there was found the relationship between electrophysical characteristics of analyzed minerals.

In addition, there was found a positive linear correlation between recovery and As content of pyrite, with $0.01\% < \alpha_{As} < 2.5\%$ (R^2=0.98), which holds at pH >10. Lastly, there is a correlation between pyrite recovery and Ni content of pyrite, with $0.015\% < \alpha_{Ni} < 1.5\%$ (R^2=0.96), which holds at 6<pH<7. From the combination of correlations revealed there was found relationships between pyrite and arsenopyrite recovery and α_{TEMF}.

Simultaneous dependence of pyrite TEMF coefficients upon arsenic and gold impurities content can be explained by particularities of auriferous minerals crystallization. According to Cabri *et al.* (1989) and Tauson *et al.* (1996) arsenic serves as gold provider on the stage of sulfide mineral lattice formation. The replacement of As by S in pyrite is accompanied by an increase of atomic spacing in the complex sulfur anion structure, which makes for the formation of dislocations. In addition, the formation of small gold inclusions in pyrite is related to the development of unstable, transitory phases involving As, which has an effect on the redistribution of existing structural defects and promotes the formation of new defects in a complete crystal. Therefore, electrophysical characteristics of arsenic pyrite, which is usually characterized by a higher than average gold content, are determined essentially by the acceptor As impurity, and the peculiar surface characteristics of arsenic pyrite crystals are related primarily to their well developed defect structure.

To summarize, the study of semiconducting, sorption and flotation properties of gold-bearing pyrite and arsenopyrite samples, followed by mathematical formalization of the relationships between different characteristics of the analyzed minerals, allowed us to identify the following regularities:
- Formatted values of monominalic electrode potentials in a neutral environment are directly proportional to eletrical resistivity of pyrite samples;
- TEMF coefficient of pyrite samples is proportional to their As, Au and Ni contents;

- Electrical resistivity of arsenopyrite samples is proportional to their Cu content and TEMF coefficient is proportional to their Au content;
- Currentless potential values of pyrites with p-type conductivity correspond to the formation of a $Fe(OH)_3$ phase on their surfaces, whereas potential values of pyrites with n-type conductivity point to preferential dissolution of surficial oxide films;
- Oxidation of buthylxanthate to dixanthogen proceeds with higher intensity on the surface of n-type pyrite, which imparts to it a higher hydrophobicity as compared to p-type pyrite;
- The proportion of chemically adsorbed collector forming metal xanthate compounds on pyrite surface increases with increasing Cu, Ni and Au contents of pyrite;
- Electrophysical properties of As-containing pyrites, which are usually characterized by a higher than average Au content, are governed by the effect of acceptor As impurity, whereas their surface characteristics are determined by their well developed defect structure.

In addition to these findings, definite pH ranges have been identified, within which the dependence of pyrite floatability on the set and concentration of different impurity species in pyrite is particularly pronounced.

4. CONCLUSIONS

Analysis and comparison of the structure of Fe molecular orbitals in pyrite and arsenopyrite, in concert with crystal-structural assessment of the ionicity of the Fe-S bond in the examined mineral samples, demonstrated that pyrite generally exhibits high redox reactivity. Based on recent data on fine gold concentration accompanied by the formation of structural defects and on the correlation between gold content of pyrite and the presence of As microinclusions in this mineral, and taking into account the possibility of formation of acceptor sulfide vacancies due to emplacement of Au into the crystal lattice of FeS_2, an ingenious methodology for the assessment of mineralogical and processing characteristics of pyrite and arsenopyrite with different genesis was developed. The newly developed methodology allowed us to identify the essential factors governing the behavior of minerals during flotation. This method also allowed to classify gold-bearing Fe and As sulfides based on a set of mineralogical and processing parameters, which would help to determine selectivity criteria for efficient selection (separation) of these minerals in flotation of gold-sulfide ores:

- More than 0.1% Cu, less than 2% As and more than 10ppm Au in pyrite, and
- Less than 0.2% As and not more than 100ppm Au in arsenopyrite.

Comparison of the elemental composition, non-stoichiometry and flotation activity of different monomineralic pyrite varieties revealed that samples with negligible impurity content are nearly stoichiometric, and show similar flotation properties. Samples with high Cu, As and Au contents are highly non-stoichiometric and readily floatable, even in a highly alkaline environment. Samples with high surface sulfur content and the most defective crystal lattices, with iron atoms substituting for sulfide vacancies, are most sensitive to depressive action of the alkali.

Formatting and linear approximation of data obtained in this study for pyrites with differing genesis have made it possible to determine the effect of impurity content, electrical resistivity and TEMF of the pyrites studied on their electrode potential and floatability, and to formalize the revealed relationships. Peak potential values of different pyrites and relative positions of potential peaks with respect to pH are governed essentially by pyrite conductivity type, whereas floatability peaks and their trend of shift towards higher alkalinity depend primarily on the set and concentration of different impurity species in pyrite.

A correlation between the type of conductivity, impurity content and amount of xanthate compounds on the surface and in the liquid phase of monomineralic pyrite and arsenopyrite suspensions detected by the extractive spectrophotometric analysis has been identified and analyzed. Experiments showed that the proportion of cuprous xanthate in sorptive collector layers on sample surfaces increases with increasing Cu content of the samples. In general, pH for pH, overall xanthate sorption on pyrite is greater than on arsenopyrite, with the difference increasing in passing from an acid environment to an alkaline one. A significant decrease in xanthate sorption on arsenopyrite is observed at pH greater than 9, whereas sorption on pyrite markedly decreases at pH greater than 11.

Variation from stoichiometry due to advent of impurity elements in mineral crystal lattices may yield both an excess (with donor Cu impurity) and a deficiency (with acceptor As impurity) of the anionic part of the mineral formula. This deviation from the stoichiometric Fe:S ratio significantly increases the proportion of chemically adsorbed collector and ensures pyrite floatability even in a strongly alkaline environment.

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